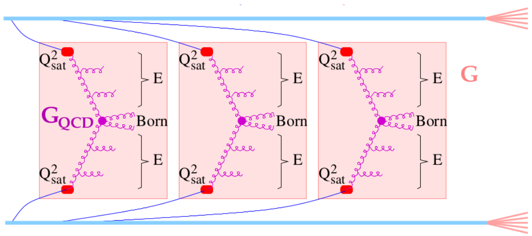

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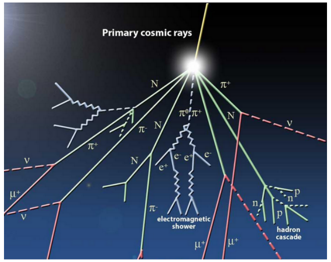

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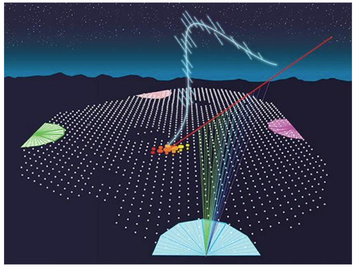

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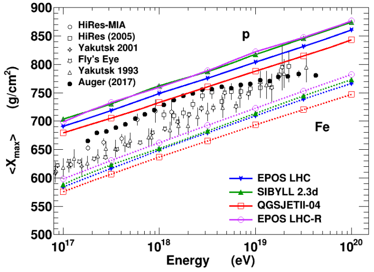


Decreasing systematic uncertainty of cosmic-ray mass through testing of models of hadronic interactions beyond LHC energies

Jakub Vícha

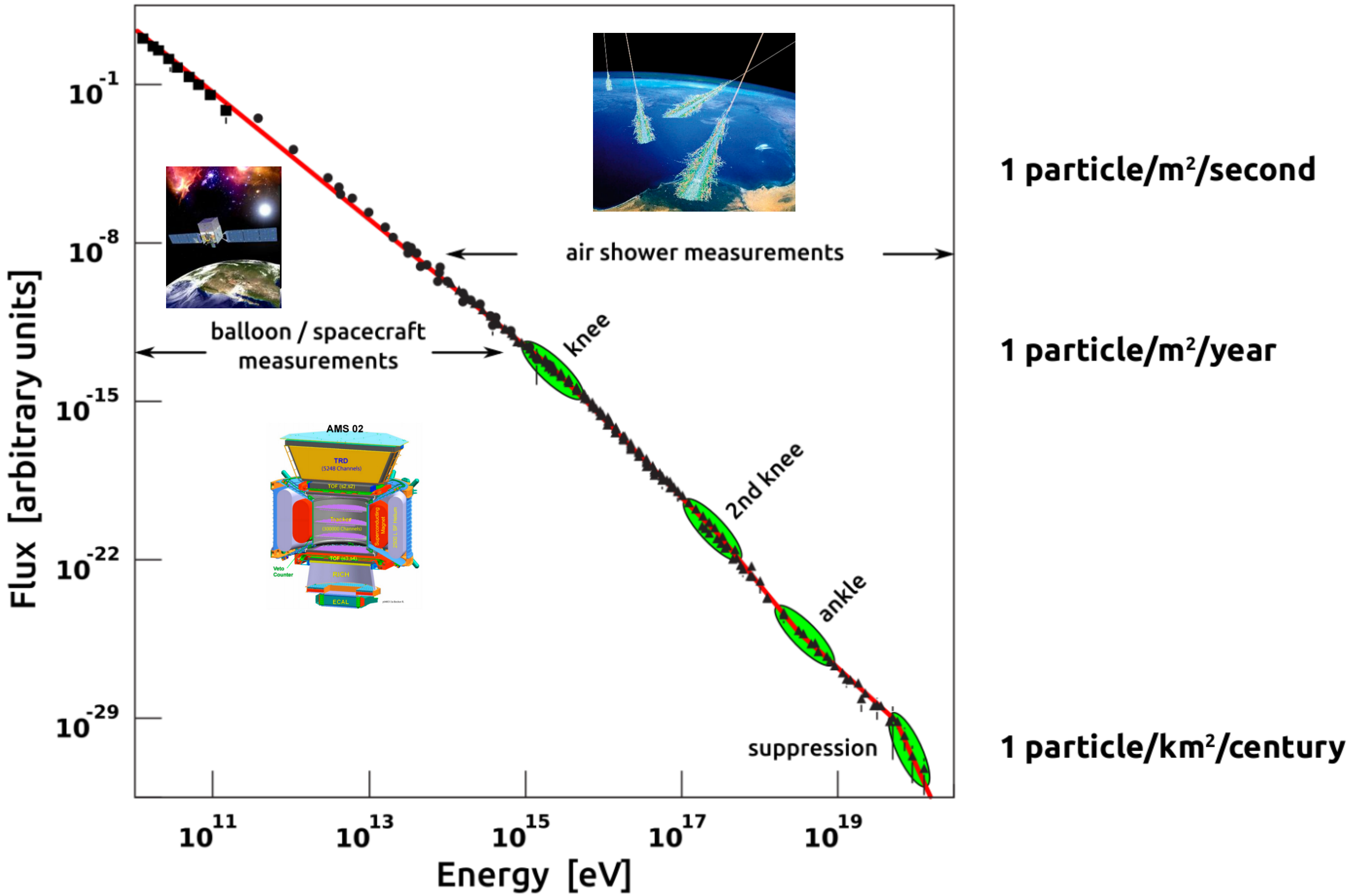
FZU
Institute of Physics of the Czech Academy of Sciences

vicha@fzu.cz

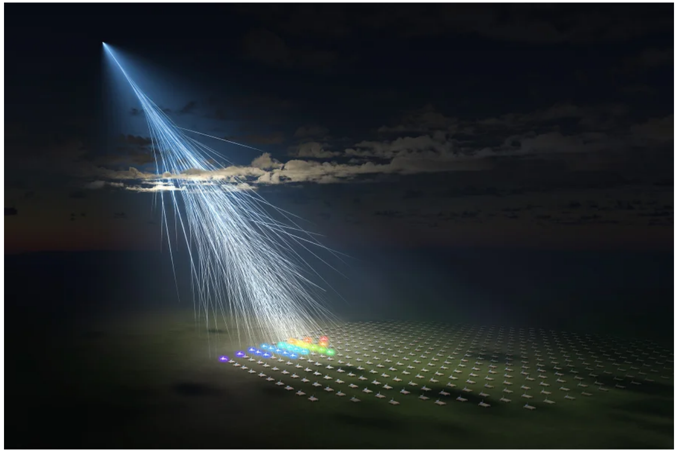
Outline of the talk

- very brief introduction into cosmic rays and air showers
- review of tests of models of hadronic interactions using air-shower data
  - muon problem in air-shower simulations
- recent reveal of a new problem in air-shower modelling regarding the depth of shower maximum (X_{max})
- consequences of this new phenomenom
  - air-shower modelling
  - cosmic-ray physics

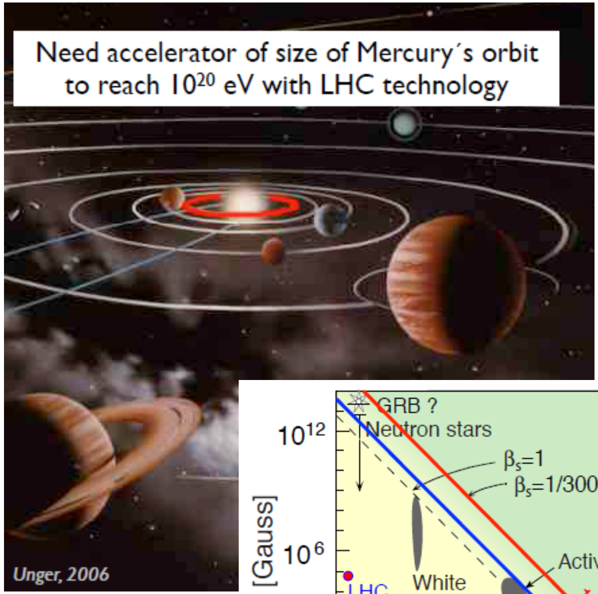
Cosmic rays

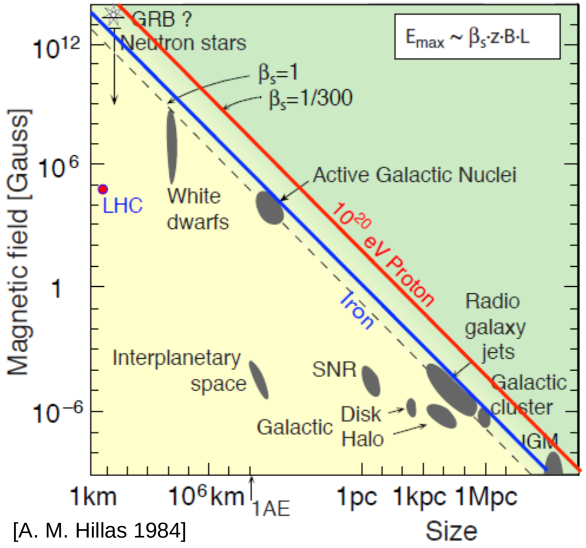


- above ~1 PeV, only indirect measurements using air showers
  - energy (spectral features)
  - mass (H...Fe... nuclei)
  - direction (anisotropies)



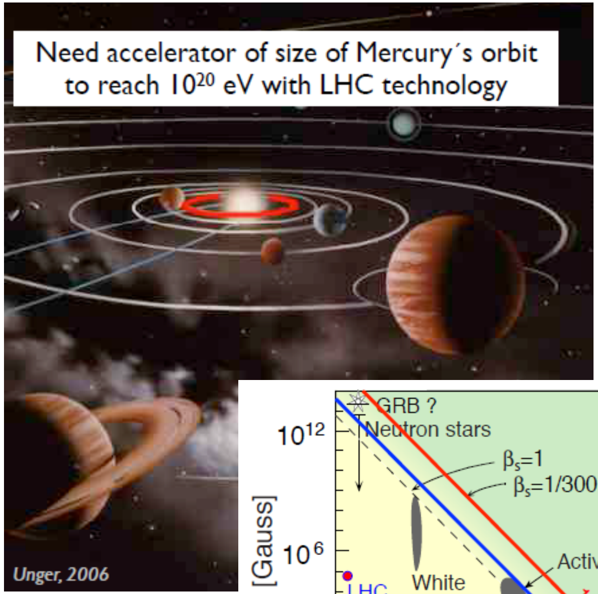
Persisting mystery beyond 10^{20} eV

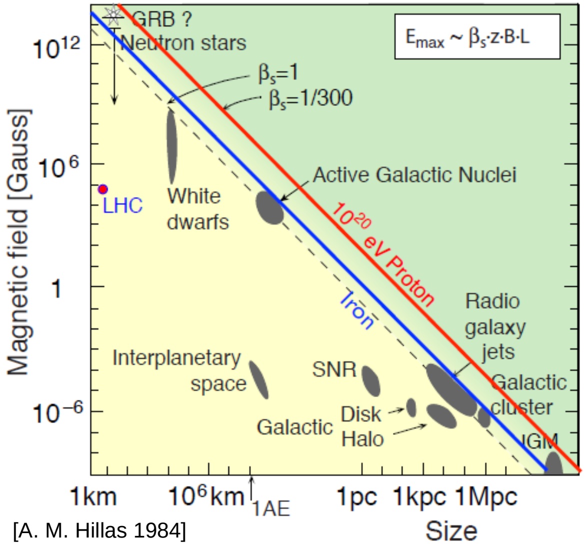




[A. M. Hillas 1984]

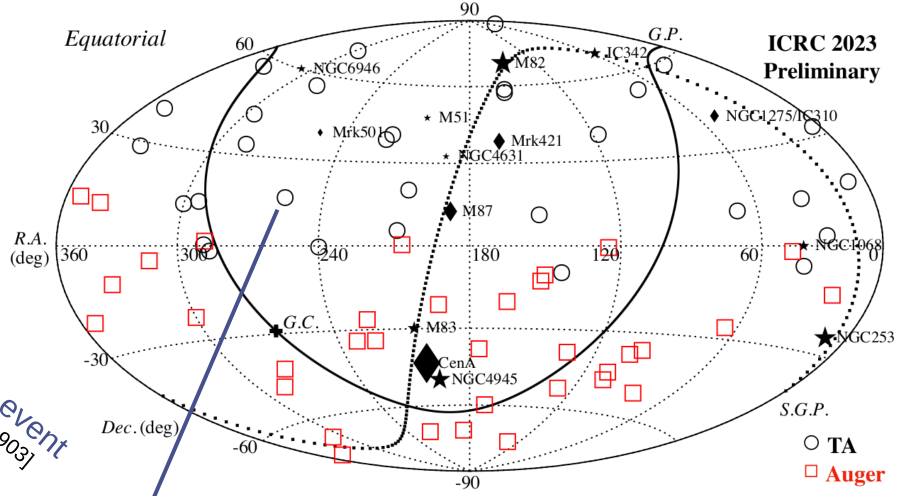
Persisting mystery beyond 10^{20} eV



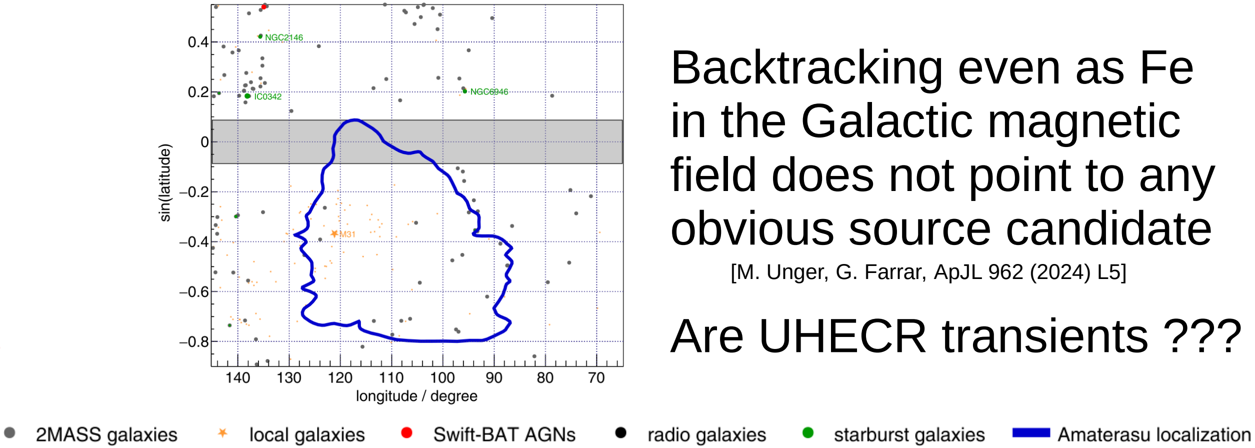


[A. M. Hillas 1984]

The most energetic event
[TA Coll., Science 382 (2023) 903]



[T. Fujii, PoS(ICRC2023)031]

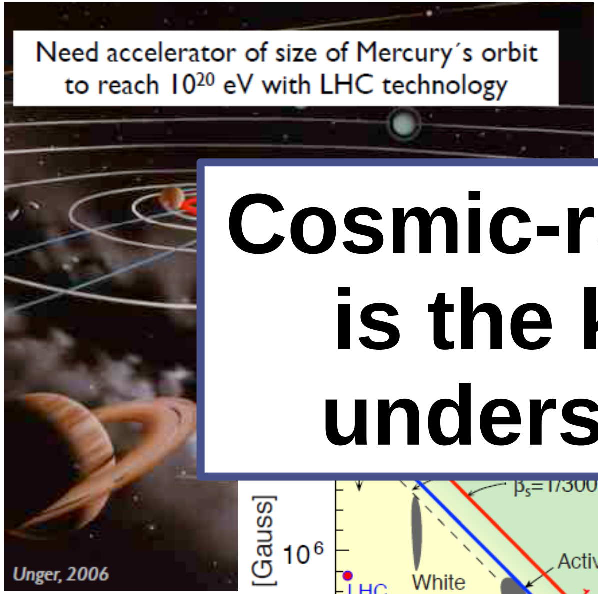


Backtracking even as Fe in the Galactic magnetic field does not point to any obvious source candidate

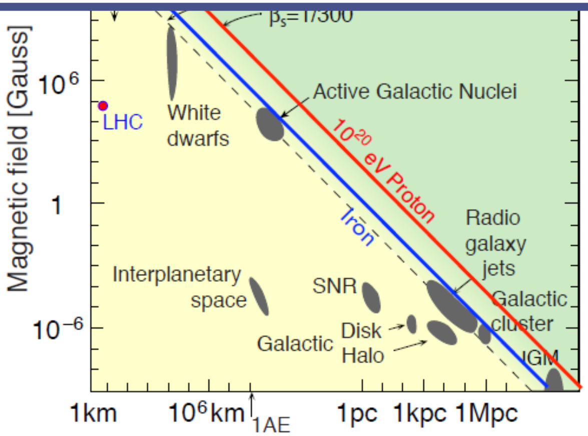
[M. Unger, G. Farrar, ApJL 962 (2024) L5]

Are UHECR transients ???

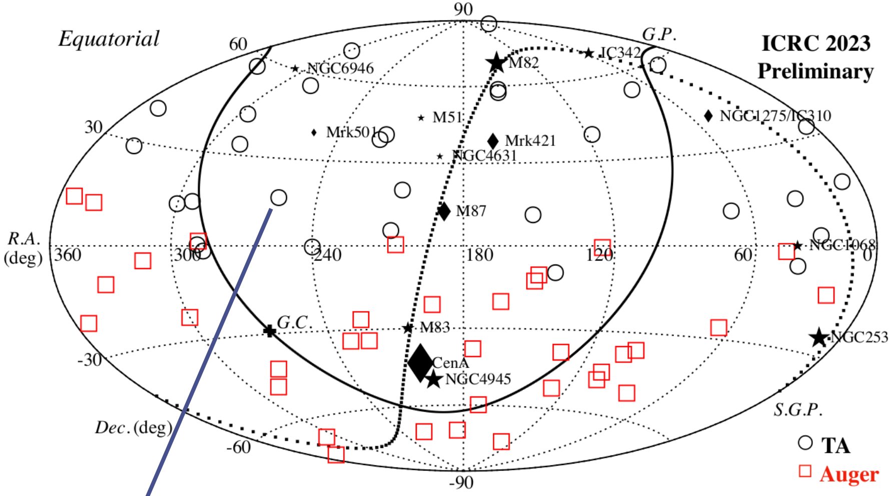
Persisting mystery beyond 10^{20} eV



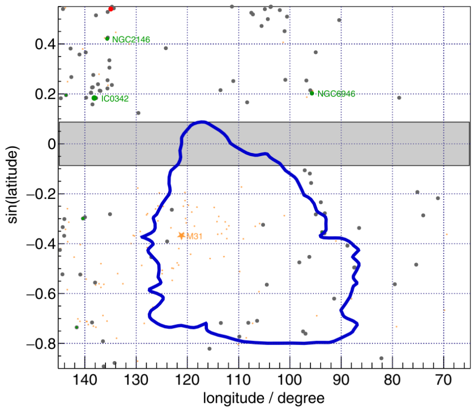
Cosmic-ray mass is the key to understand !



[A. M. Hillas 1984]



[T. Fujii, PoS(ICRC2023)031]

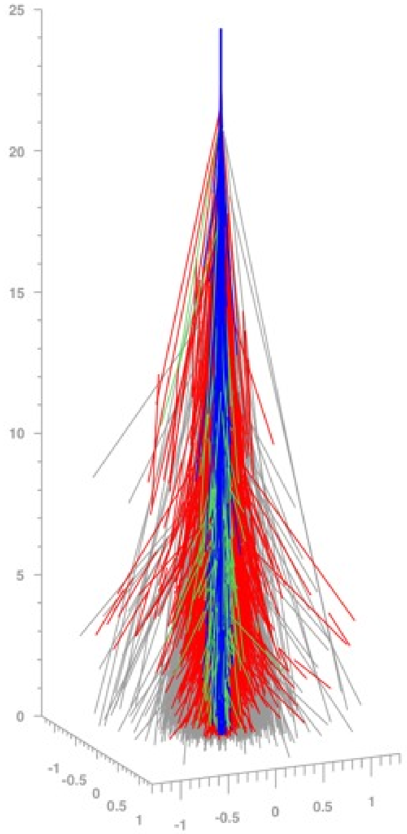


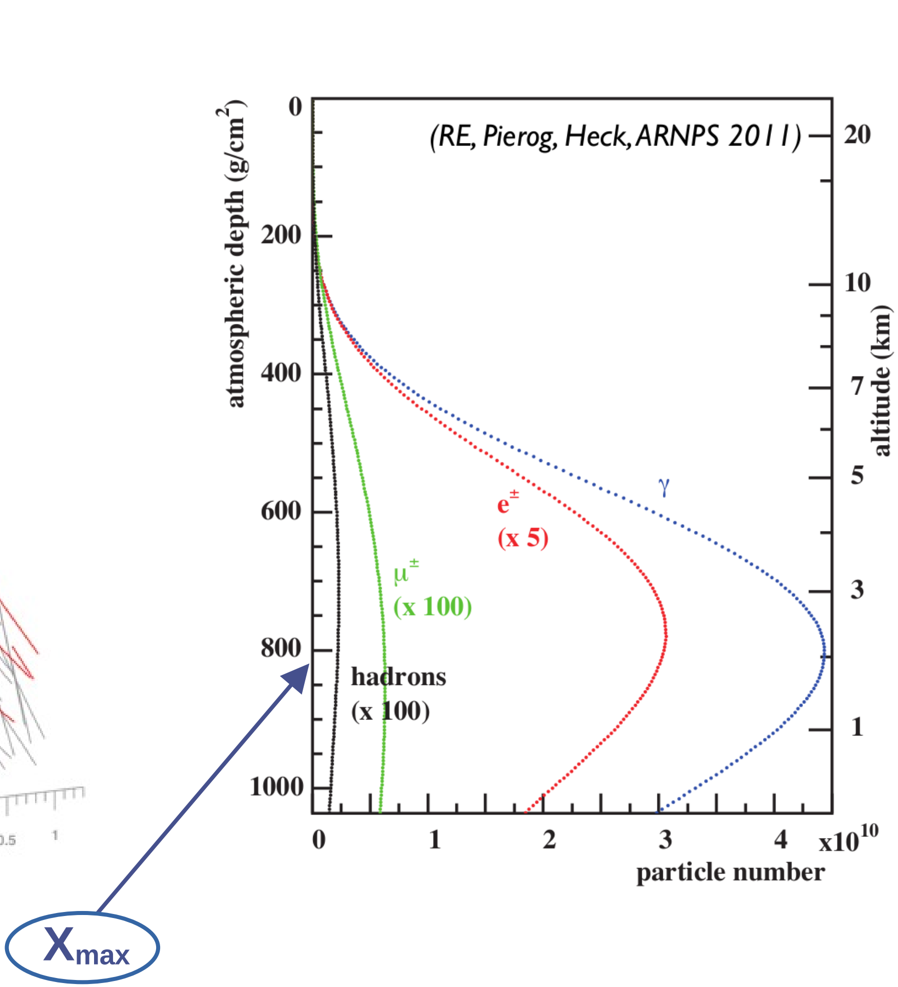
Backtracking even as Fe in the Galactic magnetic field does not point to any obvious source candidate

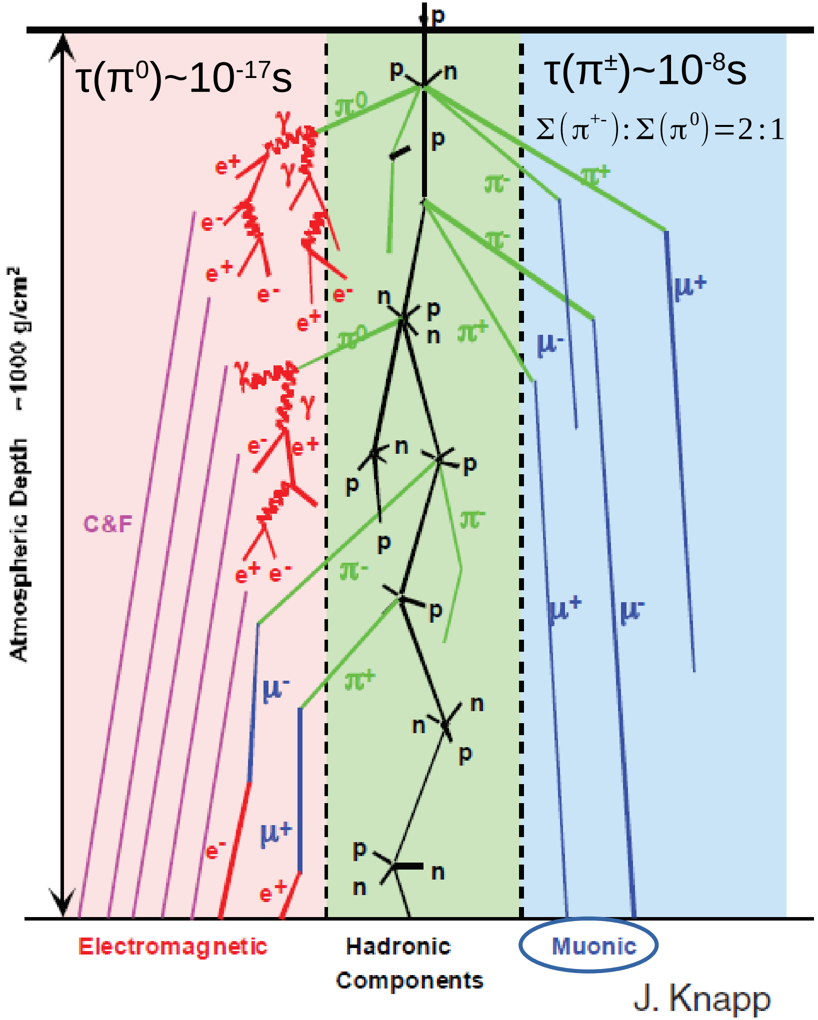
[M. Unger, G. Farrar, ApJL 962 (2024) L5]

Are UHECR transients ???

Air shower development





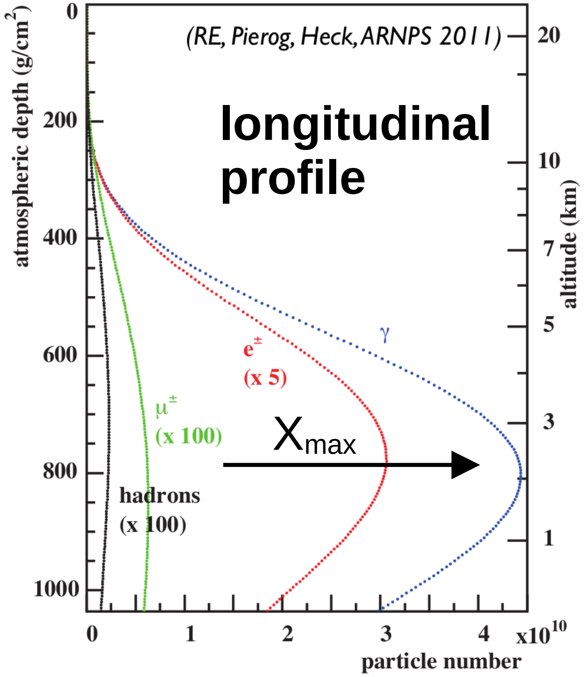


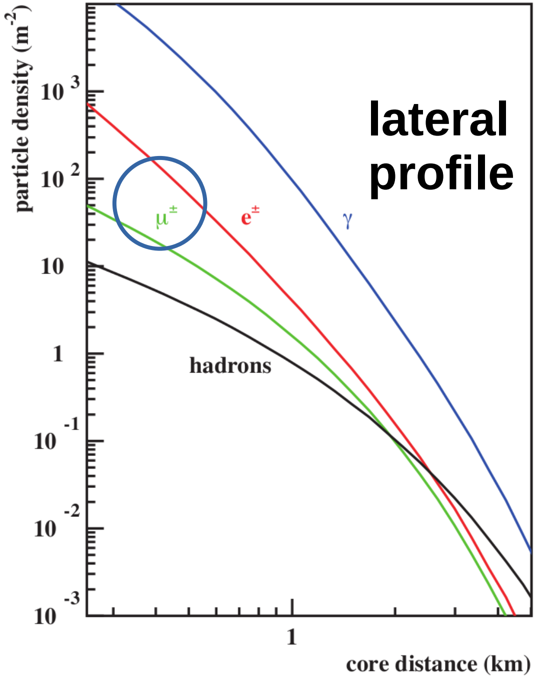
Hadronic interactions in air showers

- depth of shower maximum (X_{max})
- number of muons N_μ (decays of $\pi^\pm$)

} sensitive to primary mass ***A***

- extrapolated to higher energies and different kinematic regions than accessible
  ➔ large systematic uncertainty on interpreted *mass composition*





$$X_{max}(A) \approx X_0(E_0/A) + \lambda_r \ln[\zeta_c^e E_0/A] - \lambda_r \ln[3 N_{ch}(E_0/A)]$$

$$N_\mu(A) \approx [\zeta_c^\pi E_0/A]^\beta, \qquad \beta \approx 0.9$$

[Astropart. Phys. 22 (2005) 387]

- **X_{max}** measureable in fluorescence telecopes
  - precise, low duty cycle
- **Muons** measureable in surface detectors
  - em contamination, full duty cycle

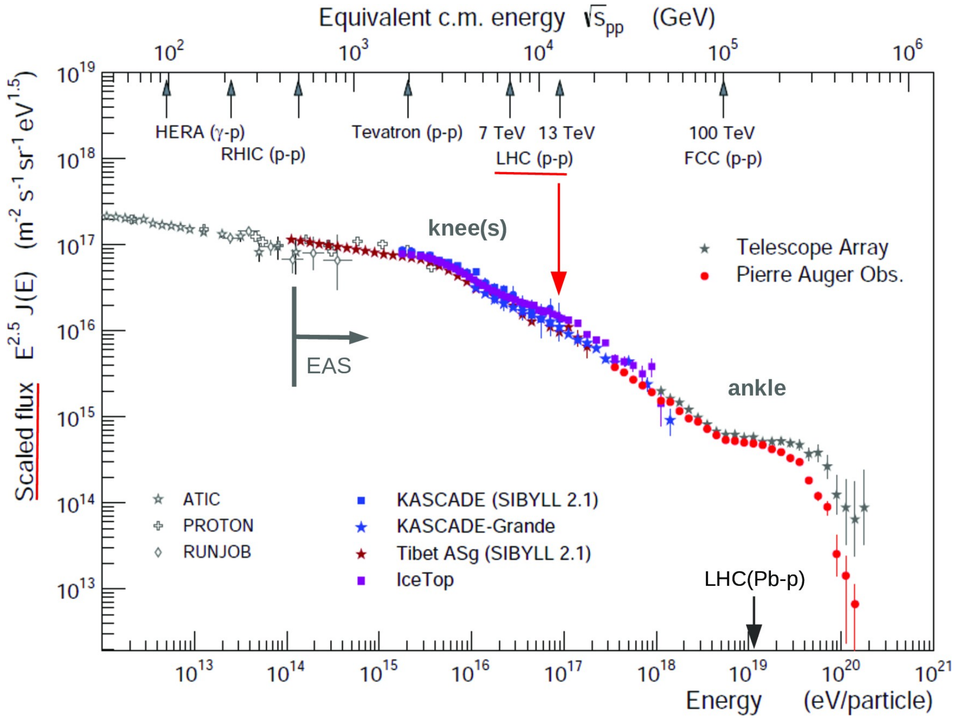
Hadronic interactions in air showers

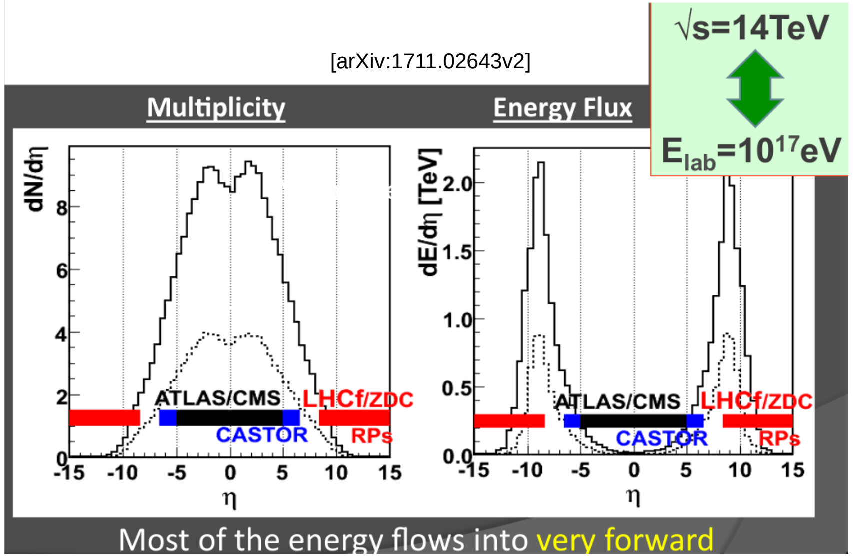
- depth of shower maximum (X_{max})
- number of muons N_μ (decays of $\pi^\pm$)

} sensitive to primary mass **A**

- extrapolated to higher energies and different kinematic regions than accessible

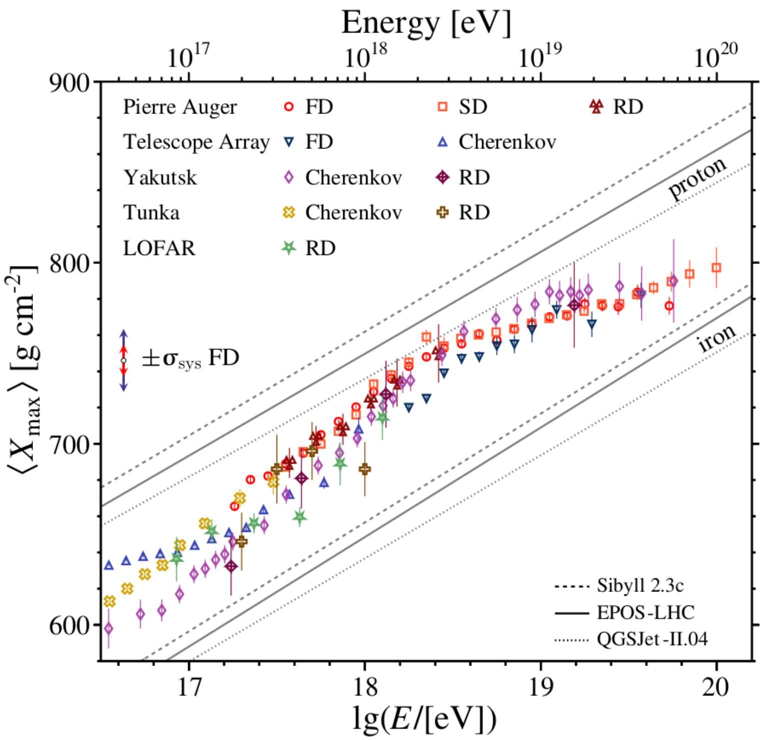
  ➔ large systematic uncertainty on interpreted *mass composition*

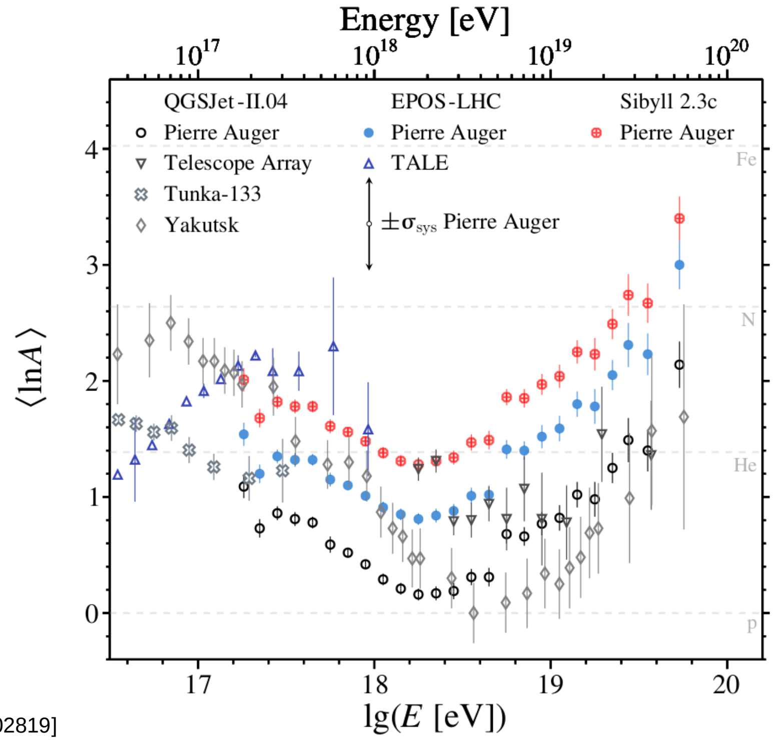




Mass composition of cosmic rays

- our knowledge is dominated by unknown systematic uncertainty of X_{max} predicted from air-shower modelling (> 20 g/cm²), compared to experimental systematics (~ 10 g/cm²)





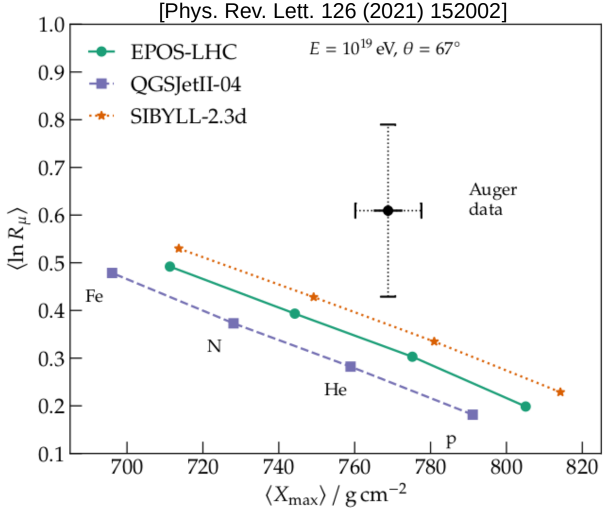
[Astropart. Phys. 149 (2023) 102819]

Testing models of hadronic interactions

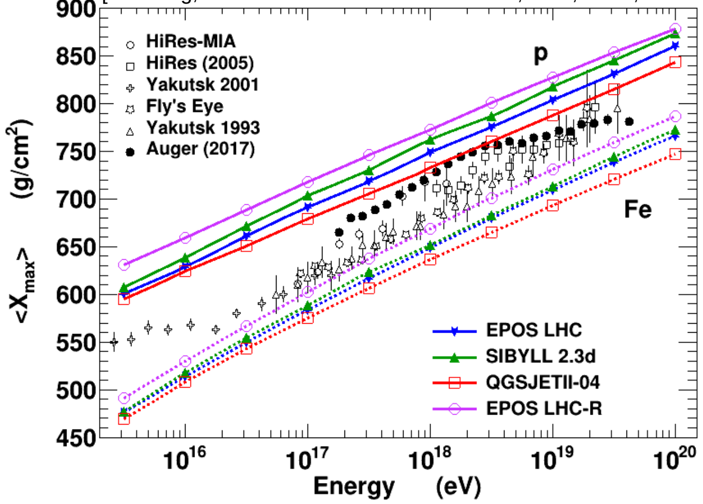
Are measured data bracketed by model predictions for protons and iron nuclei ?

The key is the consistency of observables in the interpreted mass composition at given reconstructed energy (!)

[Phys. Rev. Lett. 126 (2021) 152002]



[T. Pierog, Dec 2024 - CRs and ν in MM era, APC, Paris, France]



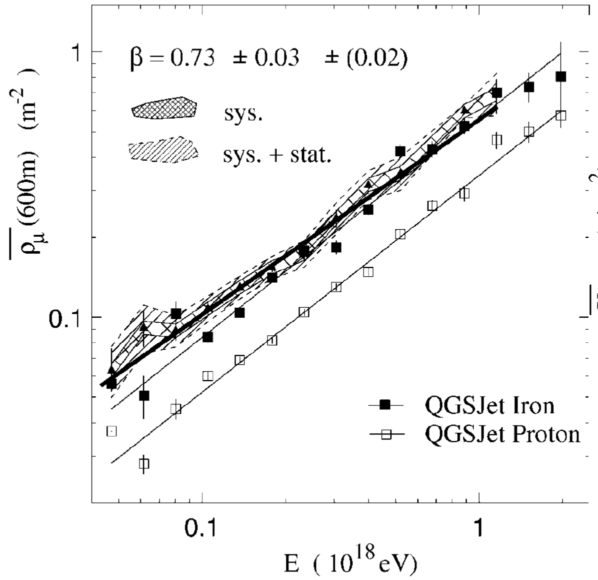
Current models of hadronic interactions available for tests:

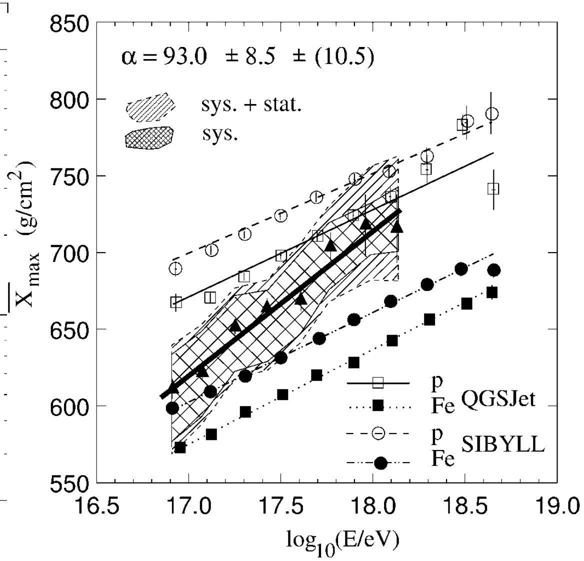
EPOS-LHC (LHCR), QGSJet II-04 (III), Sibyll 2.3d (*)

First indications of a problem to consistently describe data

HiRes-MIA experiment

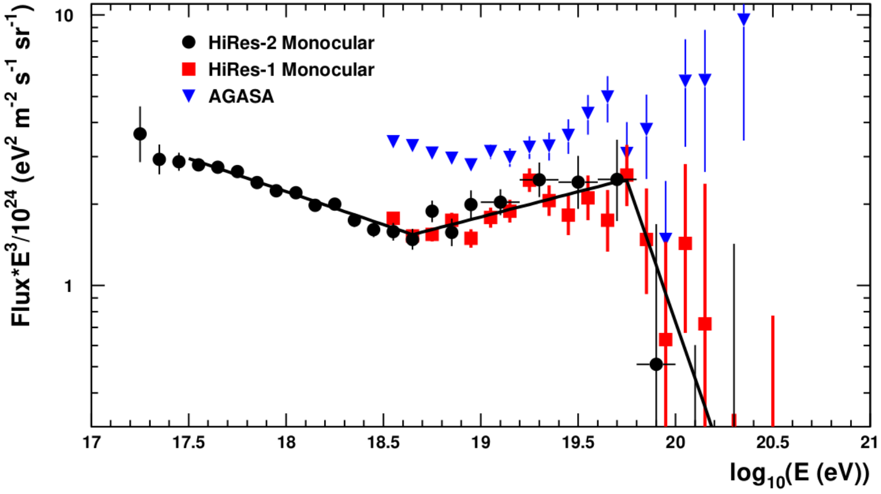
[Phys. Rev. Lett. 84 (2000) 4276]



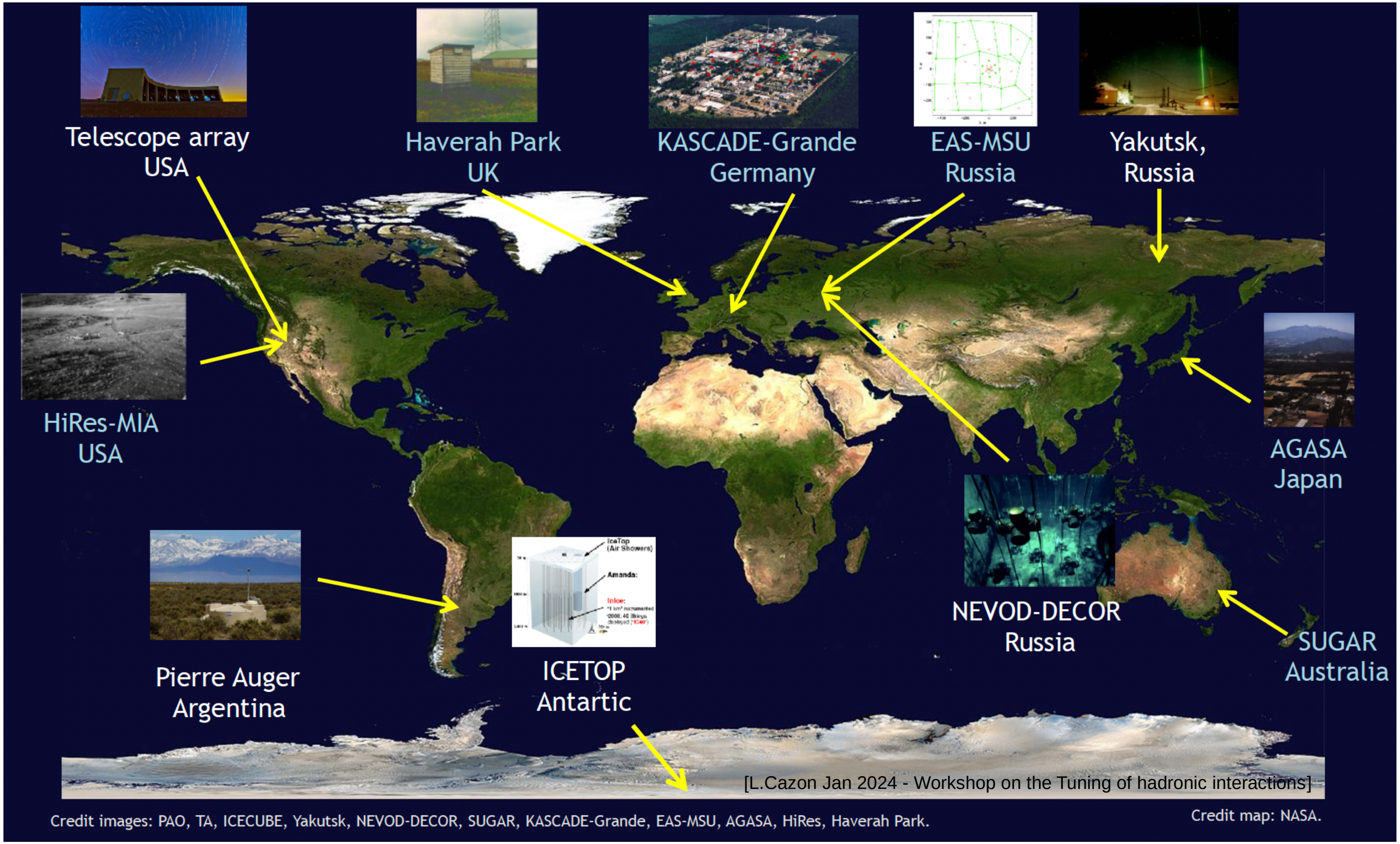


Energy estimation from muon content at AGASA

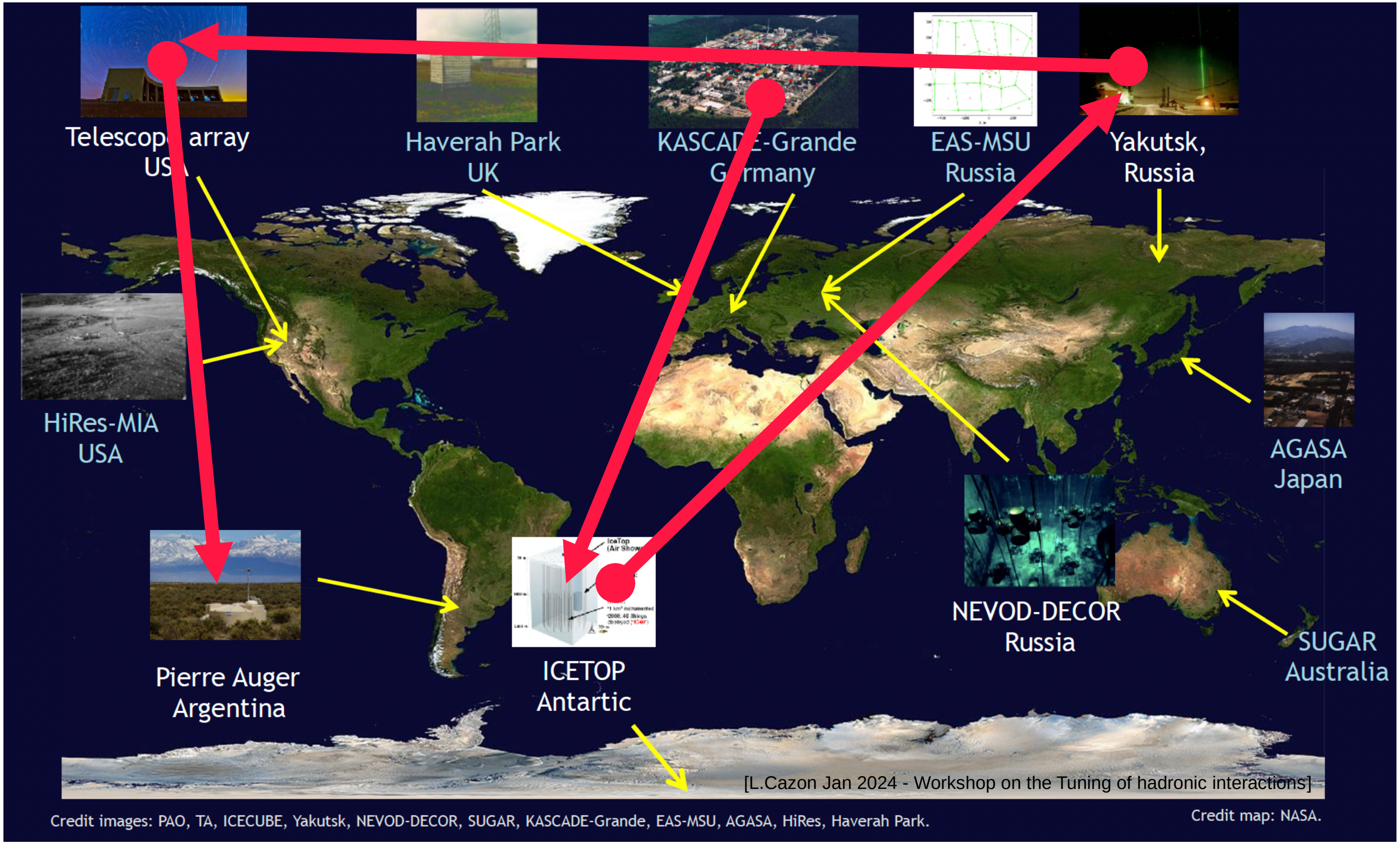
[Phys. Rev. Lett. 100 (2008) 101101]



Selected past and current air-shower experiments

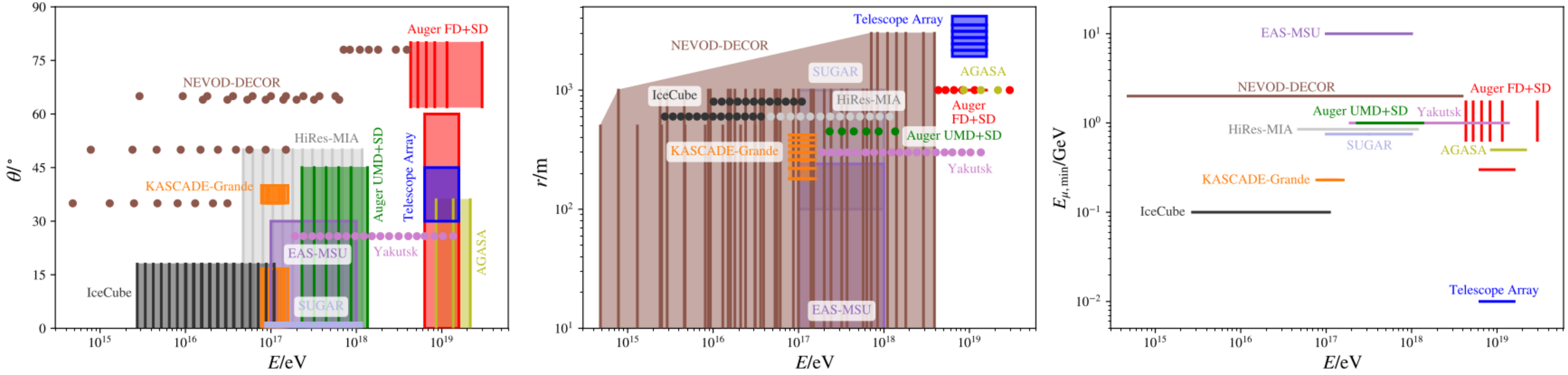


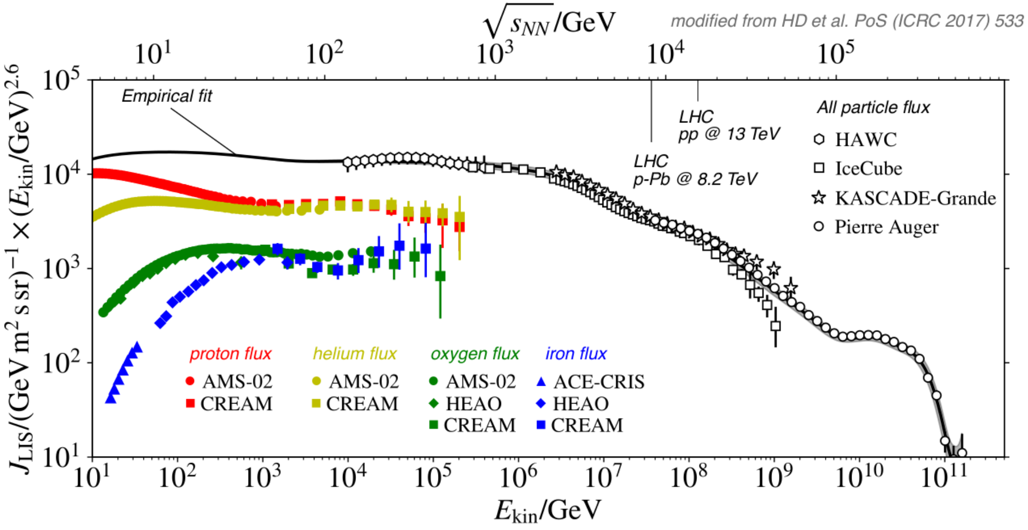
This talk: “Short tour towards higher energies“



Differencies in measurements

[Astrophys. Space Sci. 367 (2022) 3]

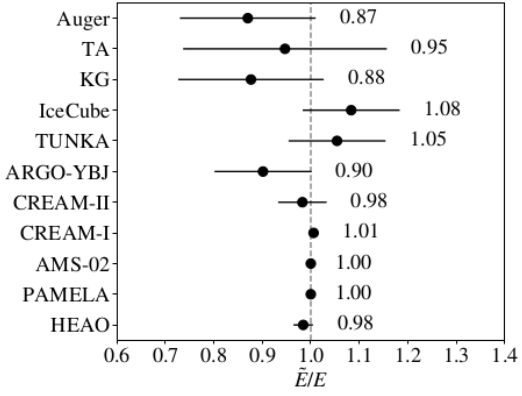




modified from HD et al. PoS (ICRC 2017) 533

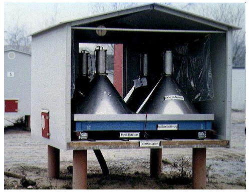
[PoS(ICRC2017)533]

Global Spline Fit (GSF)

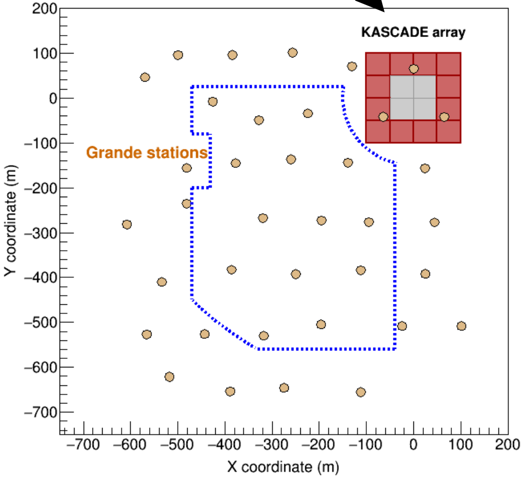


Muons at KASCADE-Grande

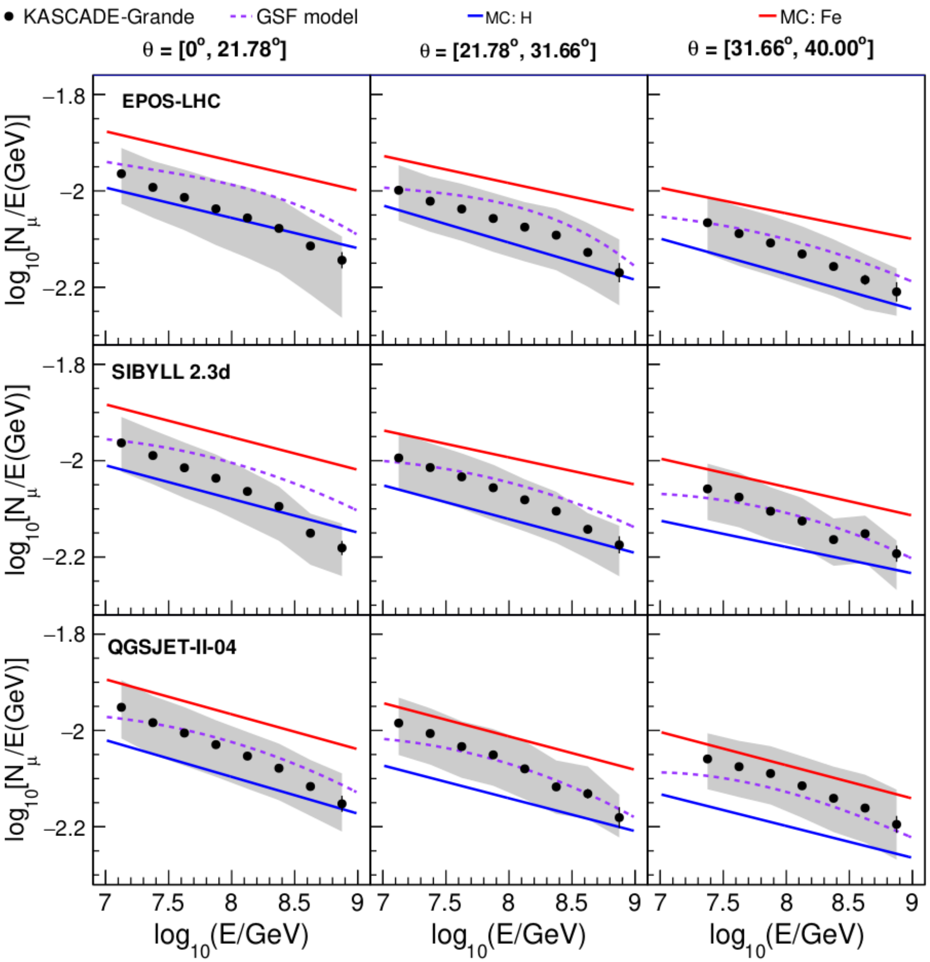
$10^{16\text{-}18}$ eV



$E_\mu > 230$ MeV



[PoS(ICRC2023)376]



Better consistency at larger zenith angles (higher muon energy)

➔ too steep muon spectra in models?

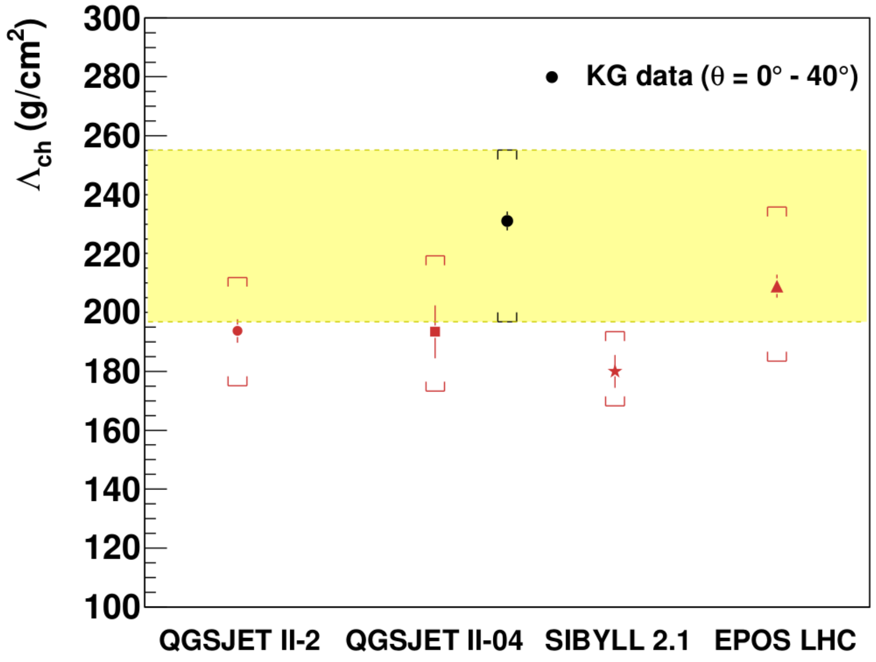
Caveat: energy scale of the Pierre Auger Observatory, GSF mass-composition model

Signal attenuation at KASCADE-Grande

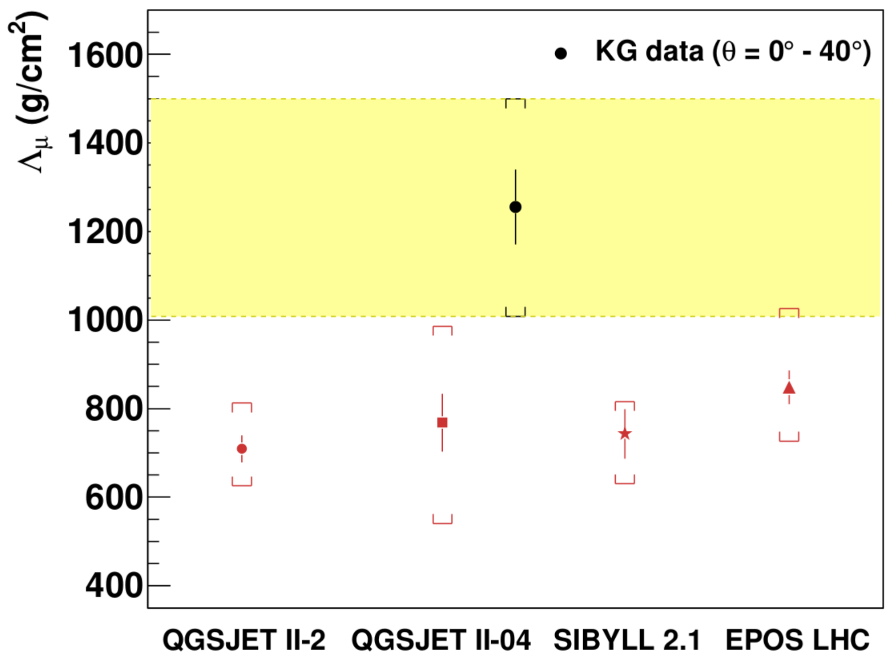
$10^{16.3\text{-}17.0}$ eV

$E_\mu > 230$ MeV

[Astropart. Phys. 95 (2017) 25]



$$N_\mu(\theta) = N_\mu^\circ \mathrm{e}^{-X_0 \sec\theta/\Lambda_\mu}$$



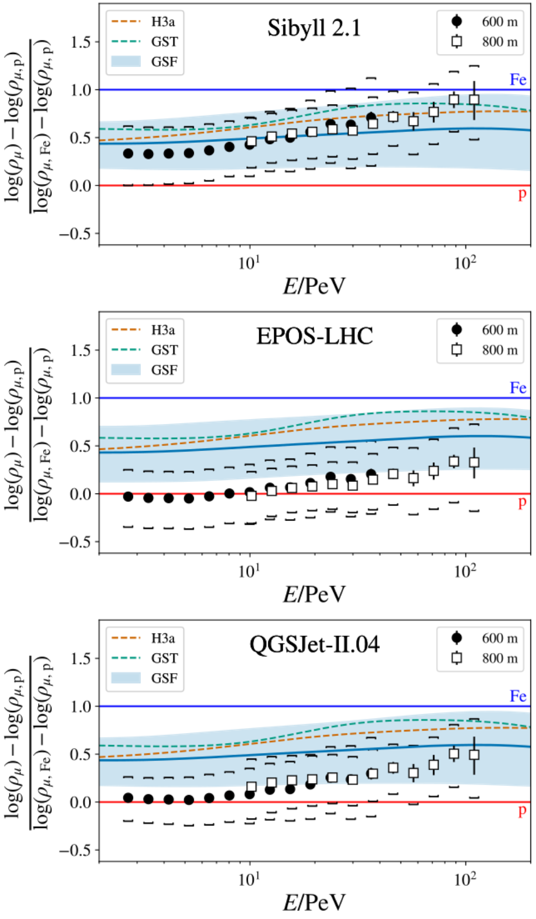
Attenuation of all charged particles consistent between data and models

Attenuation of muons in 1-2σ tension between data and models

➔ harder muon spectra in data

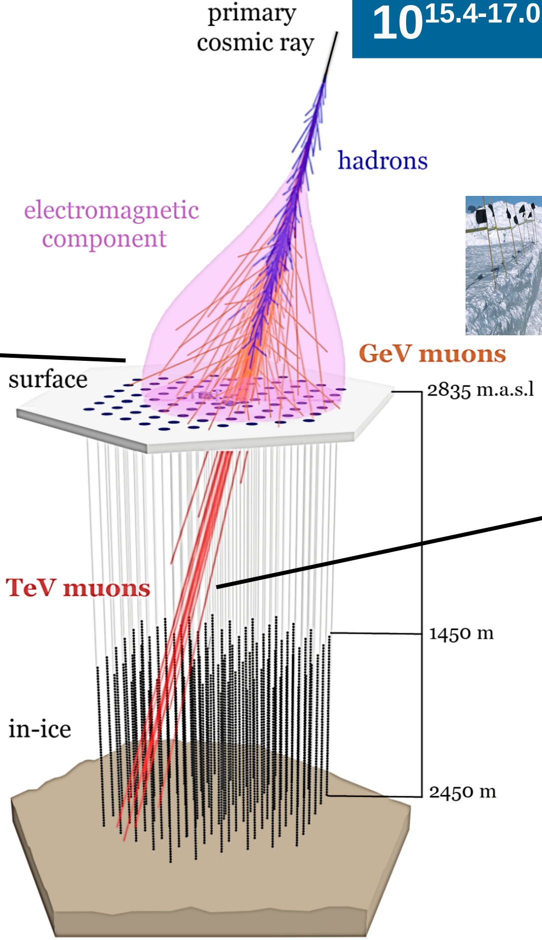
IceCube + IceTop: measurements of GeV and TeV muons

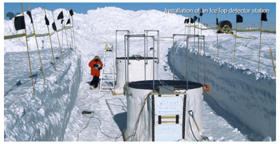
[Phys. Rev. D 106 (2022) 032010]

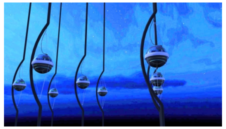


primary cosmic ray

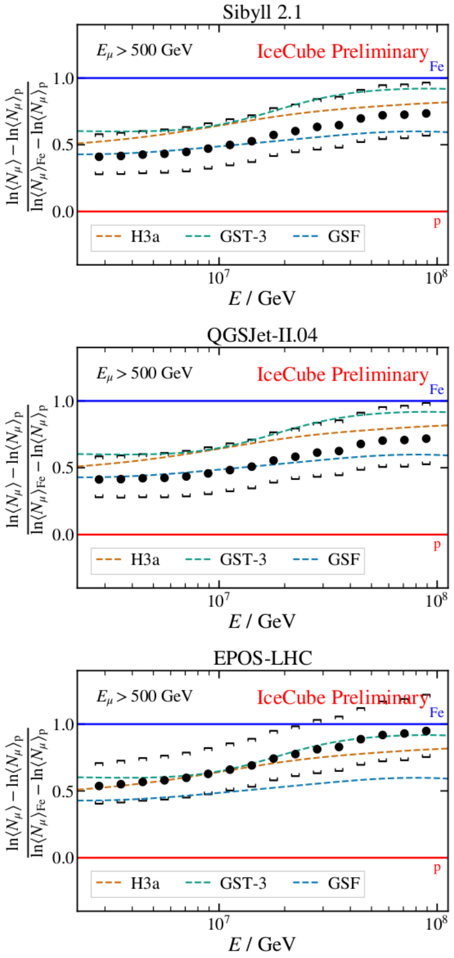
$10^{15.4\text{-}17.0}$ eV





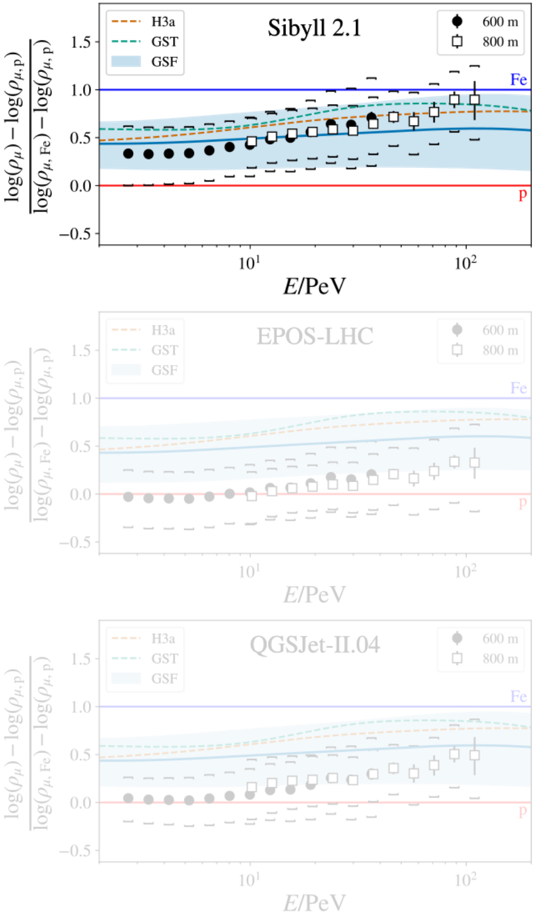


[PoS(ICRC2023)207]



IceCube + IceTop: measurements of GeV and TeV muons

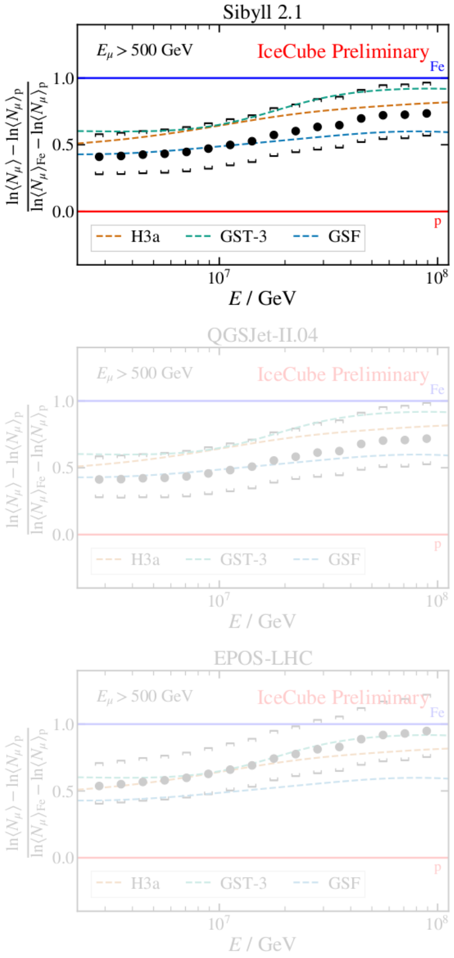
[Phys. Rev. D 106 (2022) 032010]



$10^{15.4\text{-}17.0}$ eV

The most consistent description using pre-LHC model !

[PoS(ICRC2023)207]



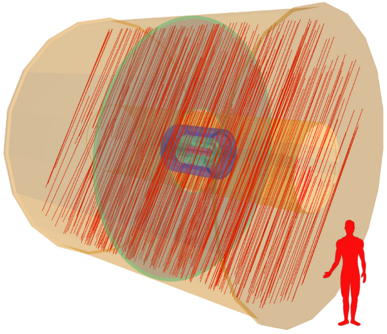
10^{16-18} eV

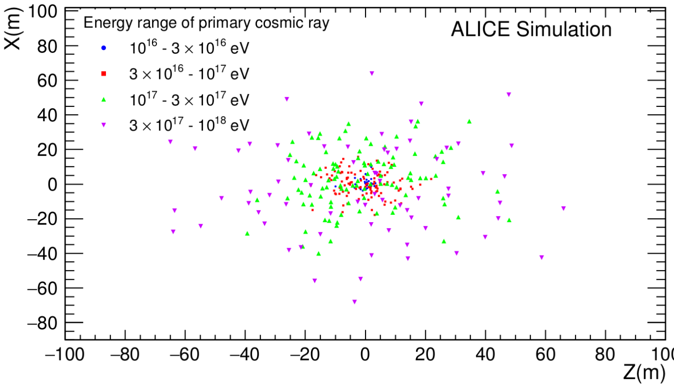
10^{15-19} eV

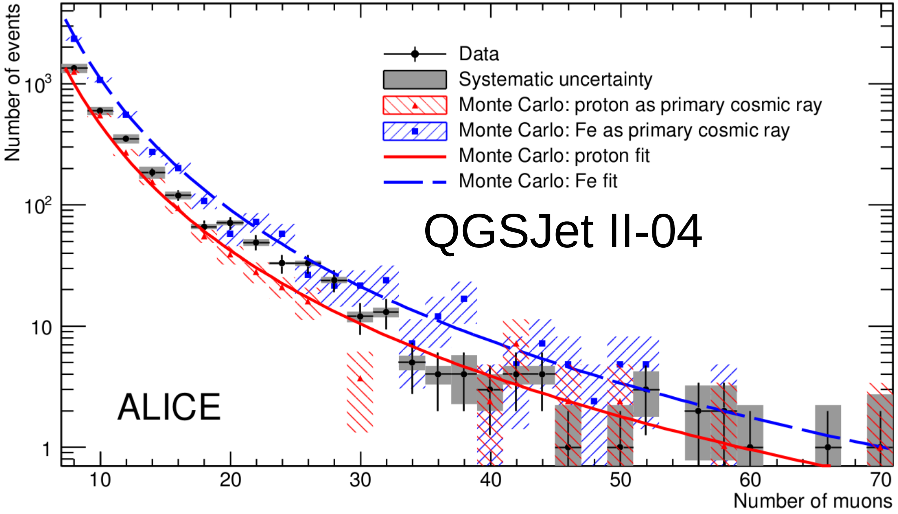
Muon bundles

ALICE

[JCAP 01 (2016) 032]

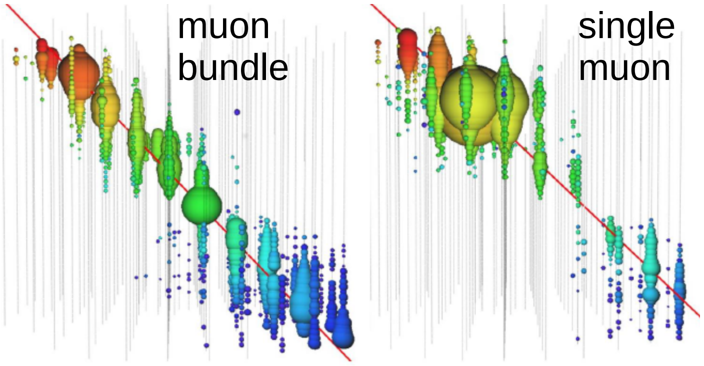




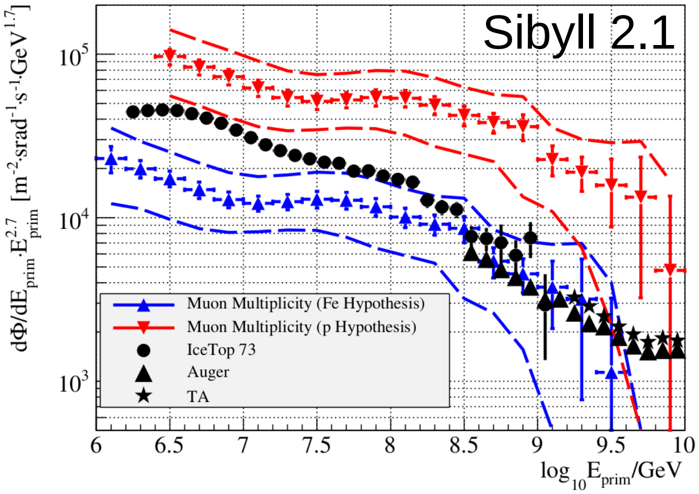


IceCube

[Astropart. Phys. 78 (2016) 1]



- no tension observed so far
- what about all new models and more statistics?

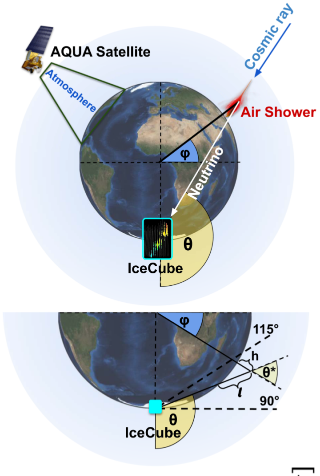


Correlation of IceCube neutrino flux with ΔT

<10^{15} eV

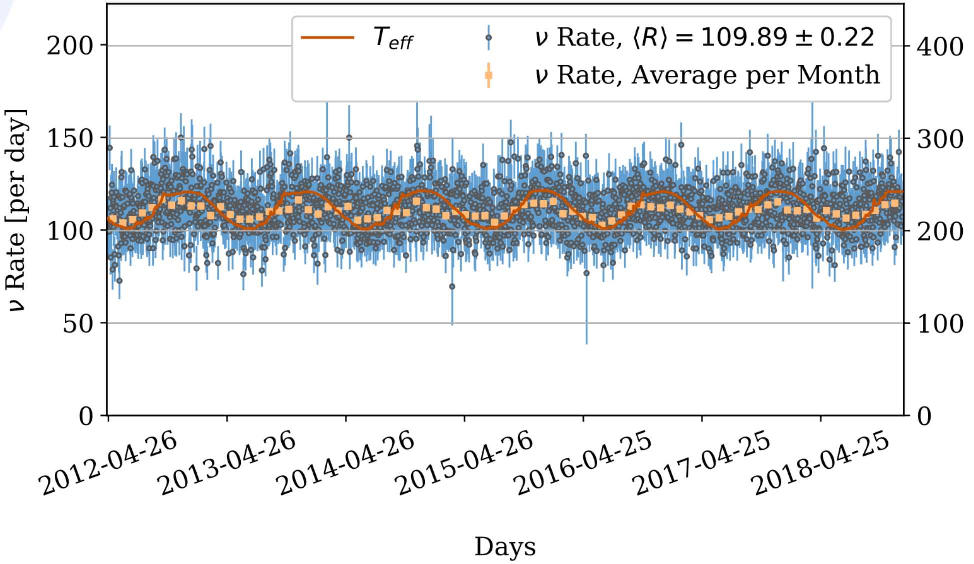
$E_\mu \approx$ TeV

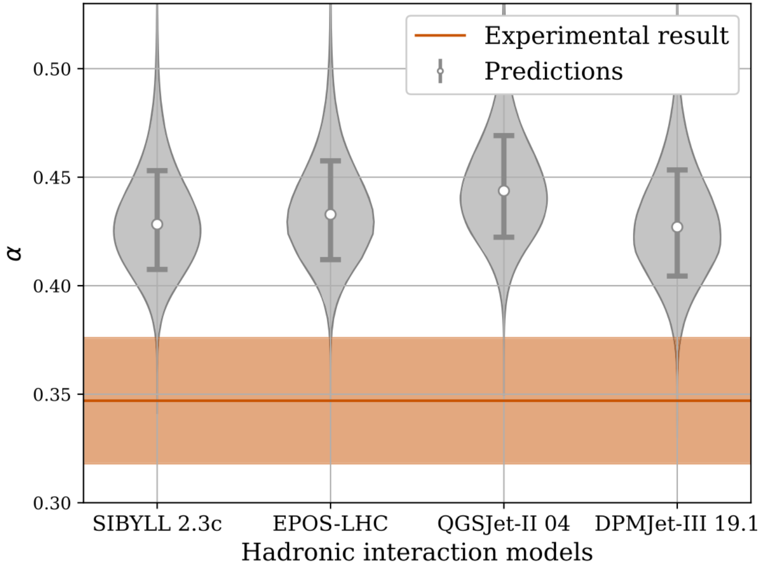
[Eur. Phys. J. C 83 (2023) 777]



- effective air temperature (T_{eff}) measured by AQUA satellite
- 262,846 ν_μ track events
  ~200-7700 GeV

$$\frac{R(t)-\bar{R}}{\bar{R}} = \alpha \frac{T_{\rm eff}(t)-\bar{T}_{\rm eff}}{\bar{T}_{\rm eff}}$$



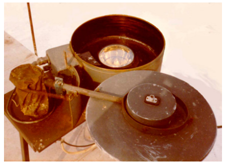


α	LLH	χ^2
Exp. result	0.347 ± 0.029	0.357 ± 0.030
MCEq	0.424 ± 0.038	0.424 ± 0.039
Analytic Appr.	0.429 ± 0.038	0.439 ± 0.039
Kaons only	0.278 ± 0.076	
Pions only	0.637 ± 0.099	

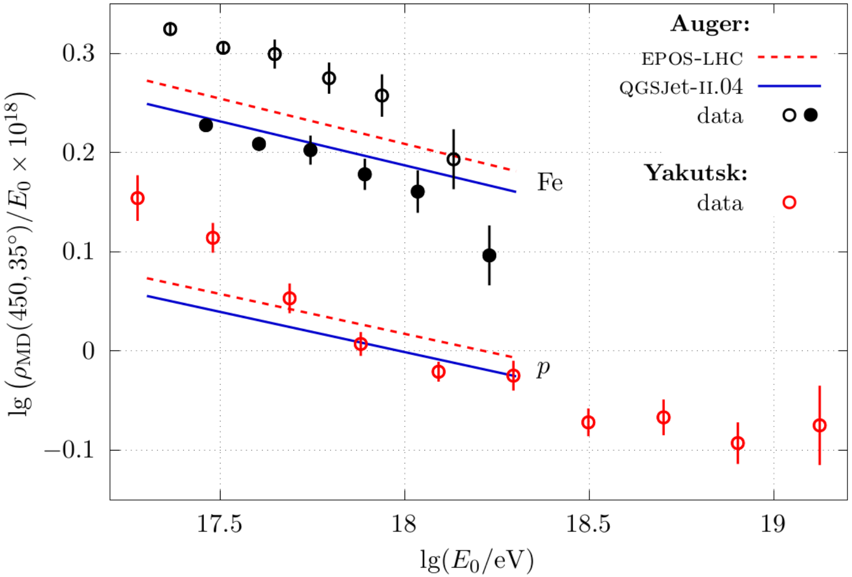
~2-3σ tension ➔ larger kaon contribution to the neutrino flux ?

10$^{17.2\text{-}19.2}$ eV

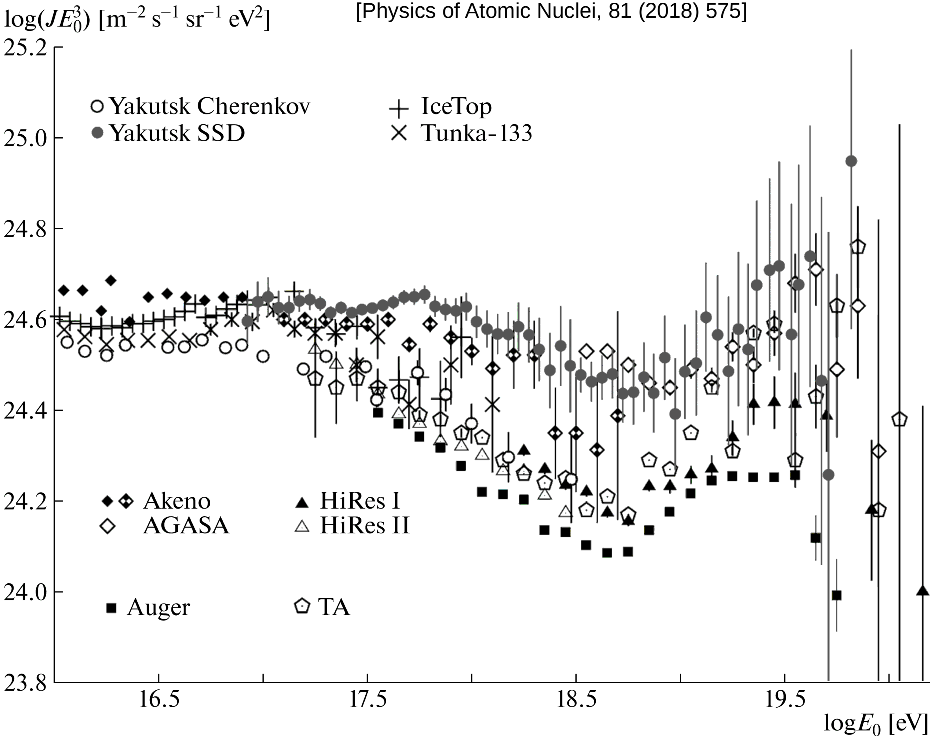
Muon density at Yakutsk



[JETP Lett. 117 (2023) 645]



[Physics of Atomic Nuclei, 81 (2018) 575]

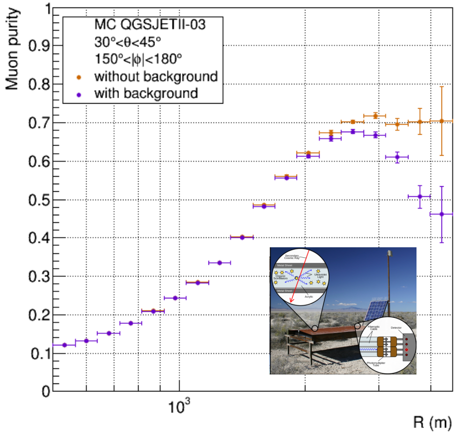


- no muon deficit and compatible with protons (excluded by Auger)
  - consequence of a difference in the energy scale ?

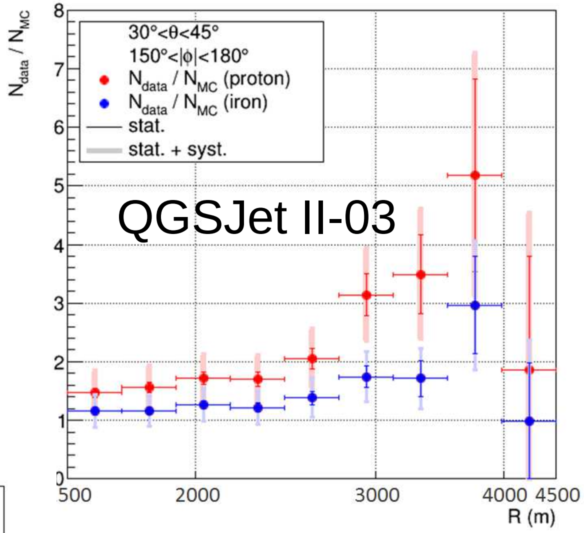
Tests at Telescope Array

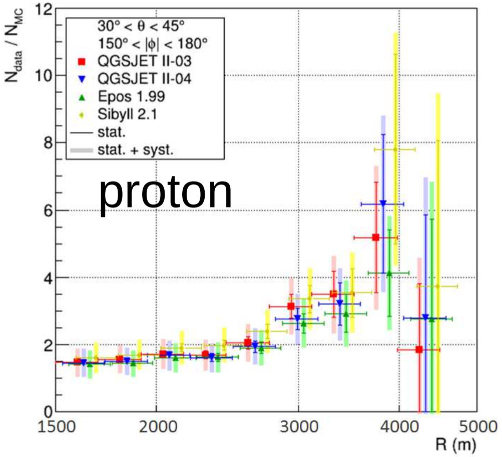
$10^{18.8-19.2}$ eV

$10^{18.2-19.0}$ eV

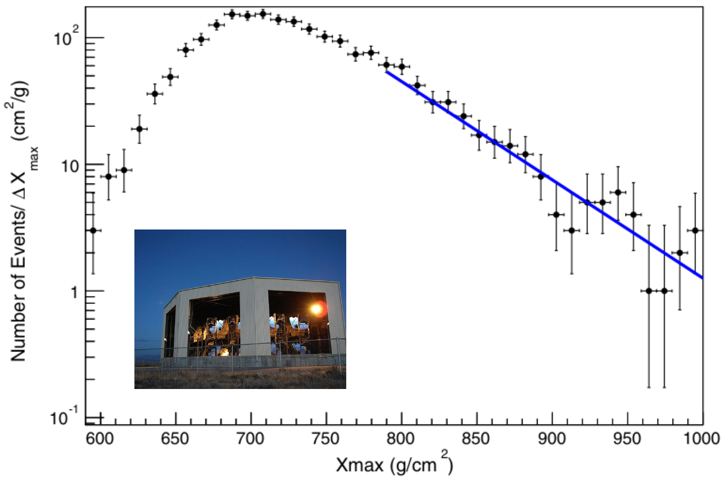


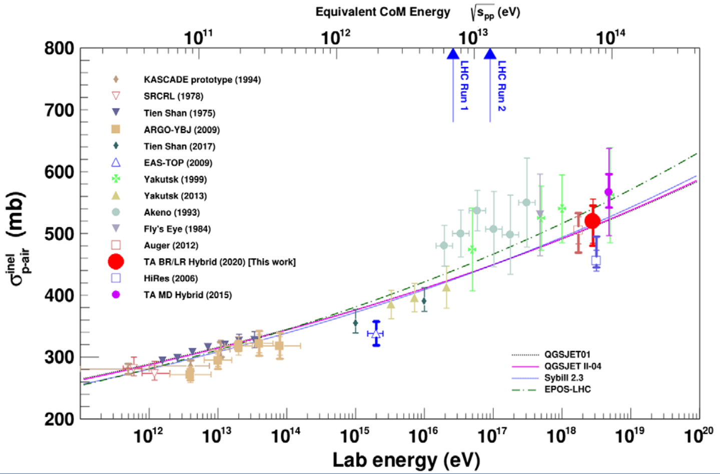
[Phys. Rev. D 98 (2018) 022002]





[Phys. Rev. D 102 (2020) 062004]



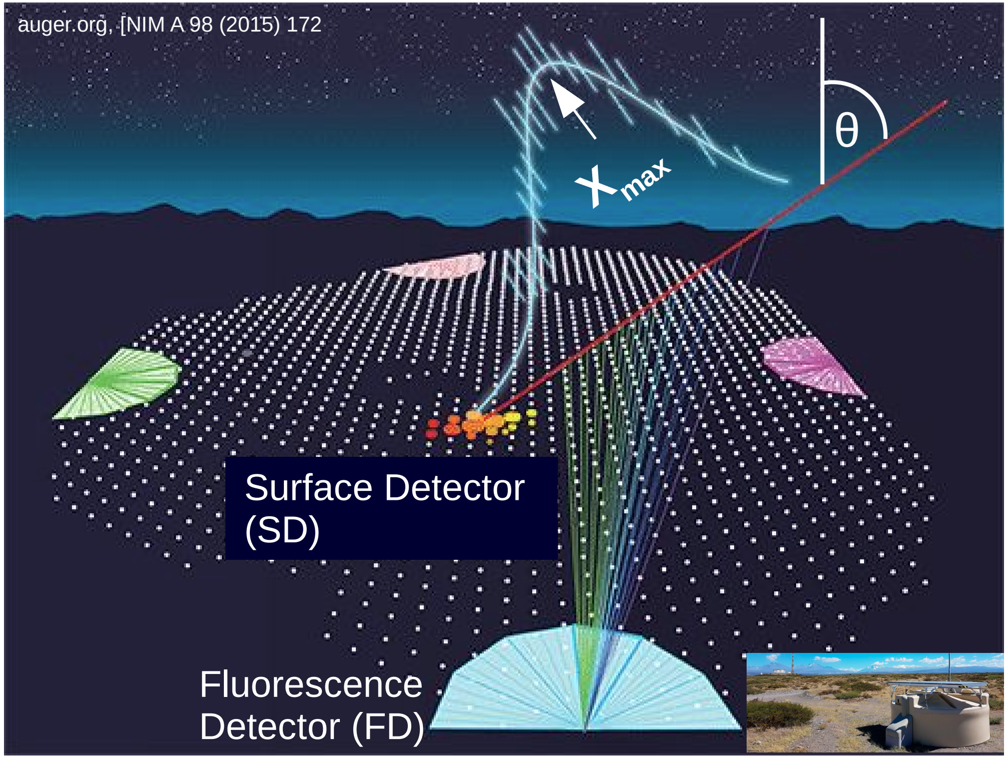


- tension with data in muons
- p-air cross-section consistent with models

The Pierre Auger Observatory - *the best instrument to study hadronic interactions above √s ≈ 50 TeV*

SD signal

- muon content
  - from buried scintillators, θ<45°
  - from N_{19}, θ>65°
- muon production depth
  - for core distance r > 1500m, θ>65°
- muon energy spectrum
  - from attenuation with θ and r
- rise time of signal vs. r



FD longitudinal profile

- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A
- p-air cross-section from tail of X_{max} distribution
- average shape of longitudinal profiles
- frequency of anomalous showers

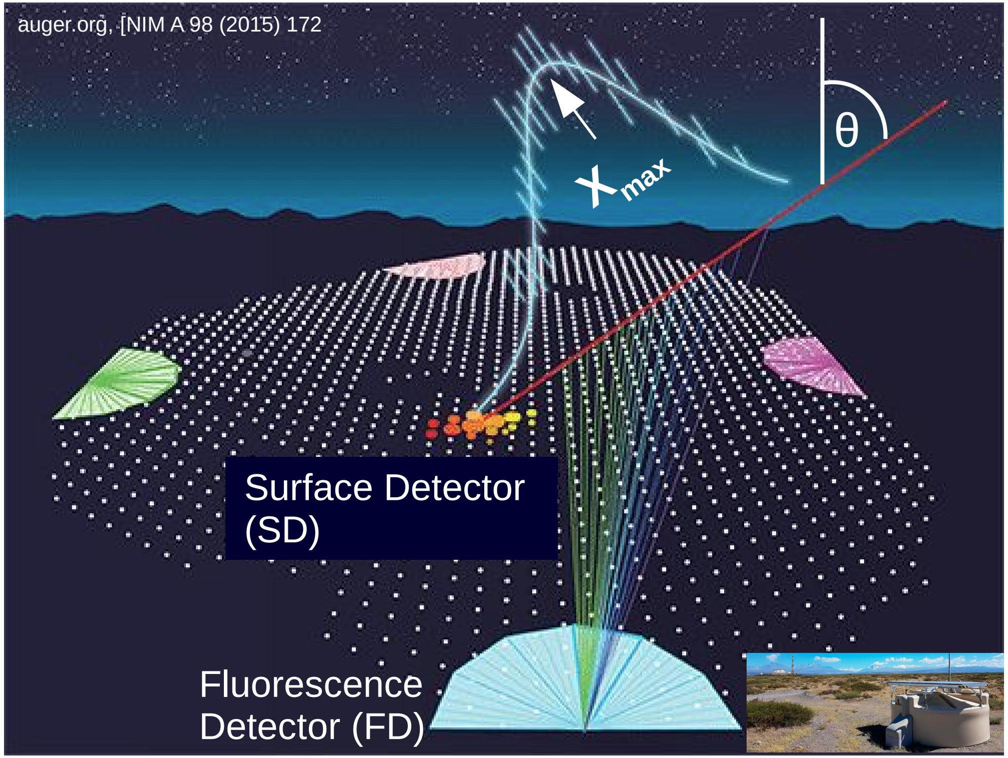
The Pierre Auger Observatory - *the best instrument to study hadronic interactions above $\sqrt{s} \approx 50$ TeV*

SD signal

- muon content
  - from buried scintillators, θ<45°
  - from N_{19}, θ>65°
- muon production depth
  - ➔ for core distance r > 1500m, θ>65°

  [Phys. Rev. D 90 (2014) 012012]
- muon energy spectrum
  - from attenuation with θ and r
- rise time of signal vs. r

  [Phys. Rev. D 96 (2017) 122003]



not covered here, see references and backup slides

FD longitudinal profile

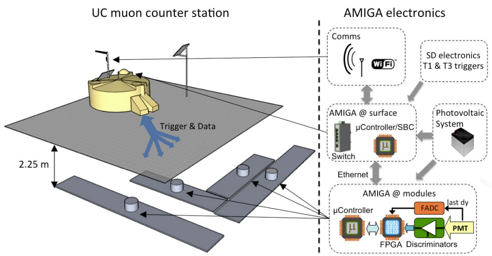
- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A
- p-air cross-section from tail of X_{max} distribution
- average shape of longitudinal profiles

  [JCAP 03 (2019) 018]
- frequency of anomalous showers

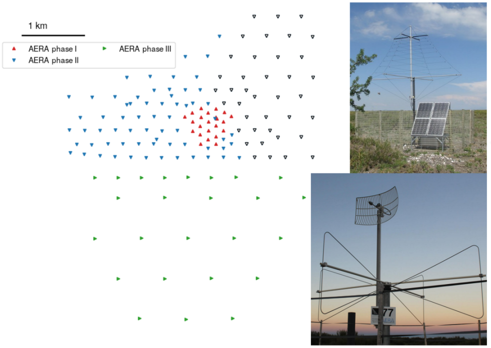
  [EPJ Web of Conferences 144 (2017) 01009]

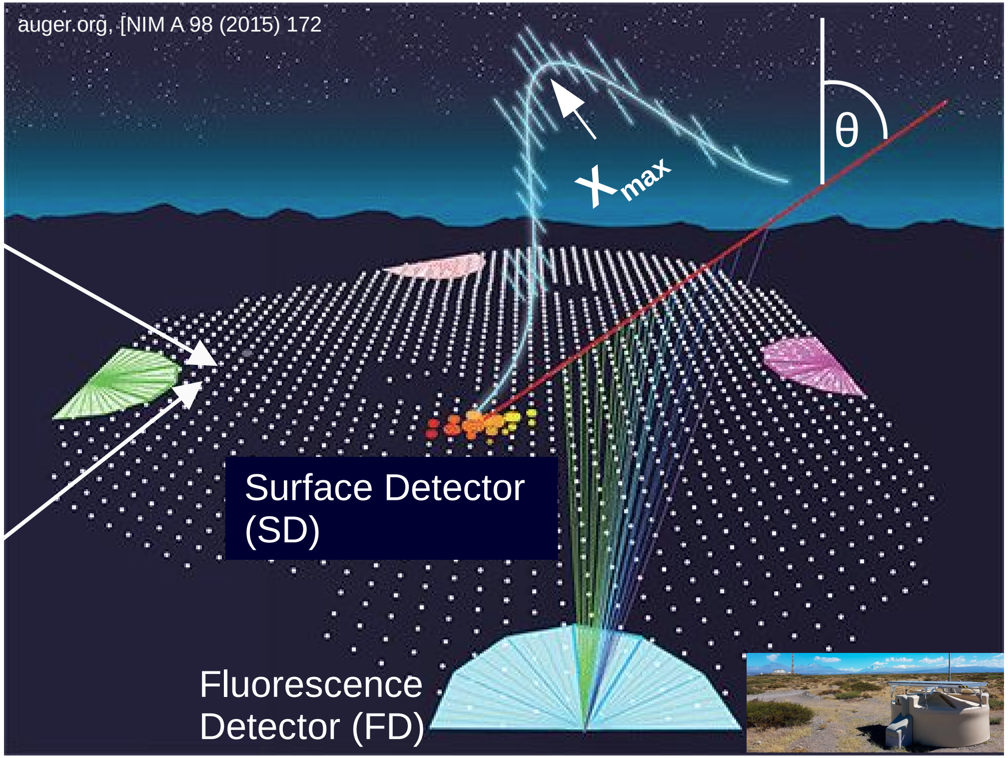
The Pierre Auger Observatory - *the best instrument to study hadronic interactions above √s ≈ 50 TeV*

+ UMD

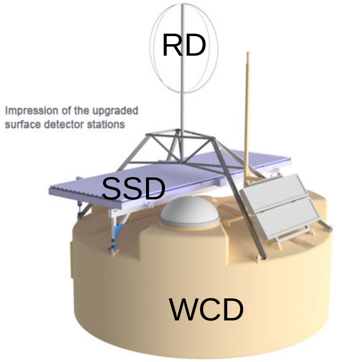


+ AERA





+ AugerPrime



Especially for combination of SD and FD observables !
+ more to come in near future

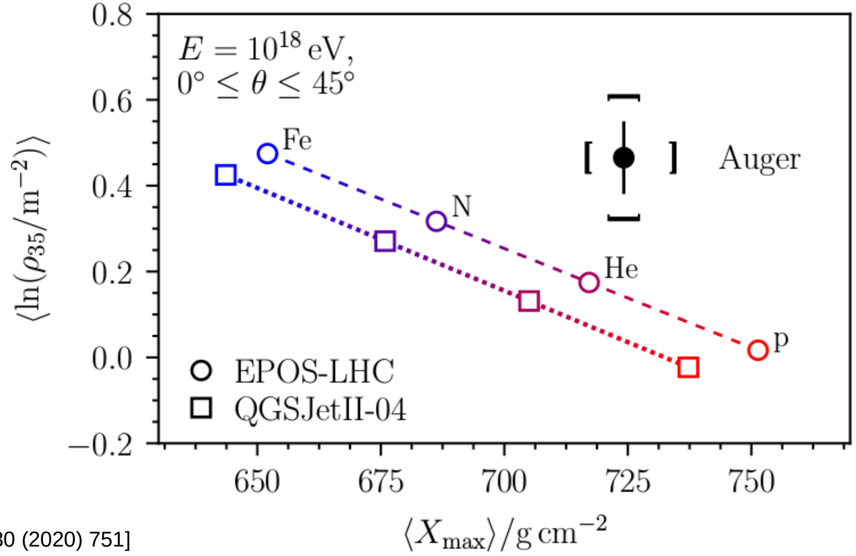
Observables relevant to hadronic interaction models

SD signal

- muon content
  - ➔ from buried scintillators, θ<45°
  - ➔ from N_{19}, θ>65°
- muon production depth
  - ➔ for core distance r > 1500m, θ>65°

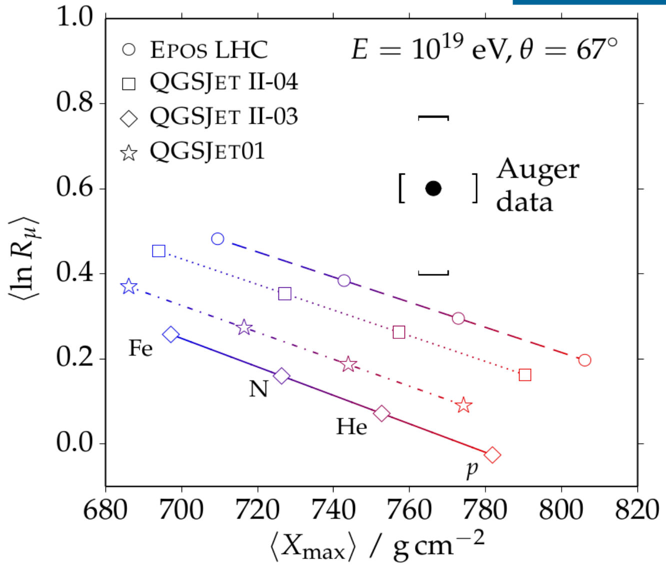
10^{18} eV

[Eur. Phys. J. C 80 (2020) 751]

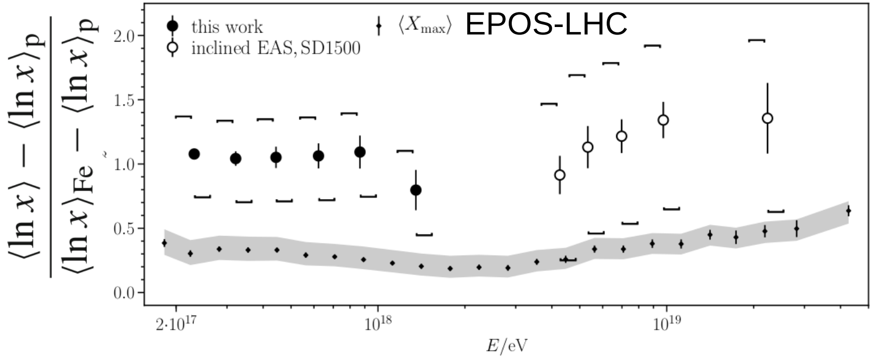


[Phys. Rev. D 91 (2015) 032003]

10^{19} eV



[Eur. Phys. J. C 80 (2020) 751]



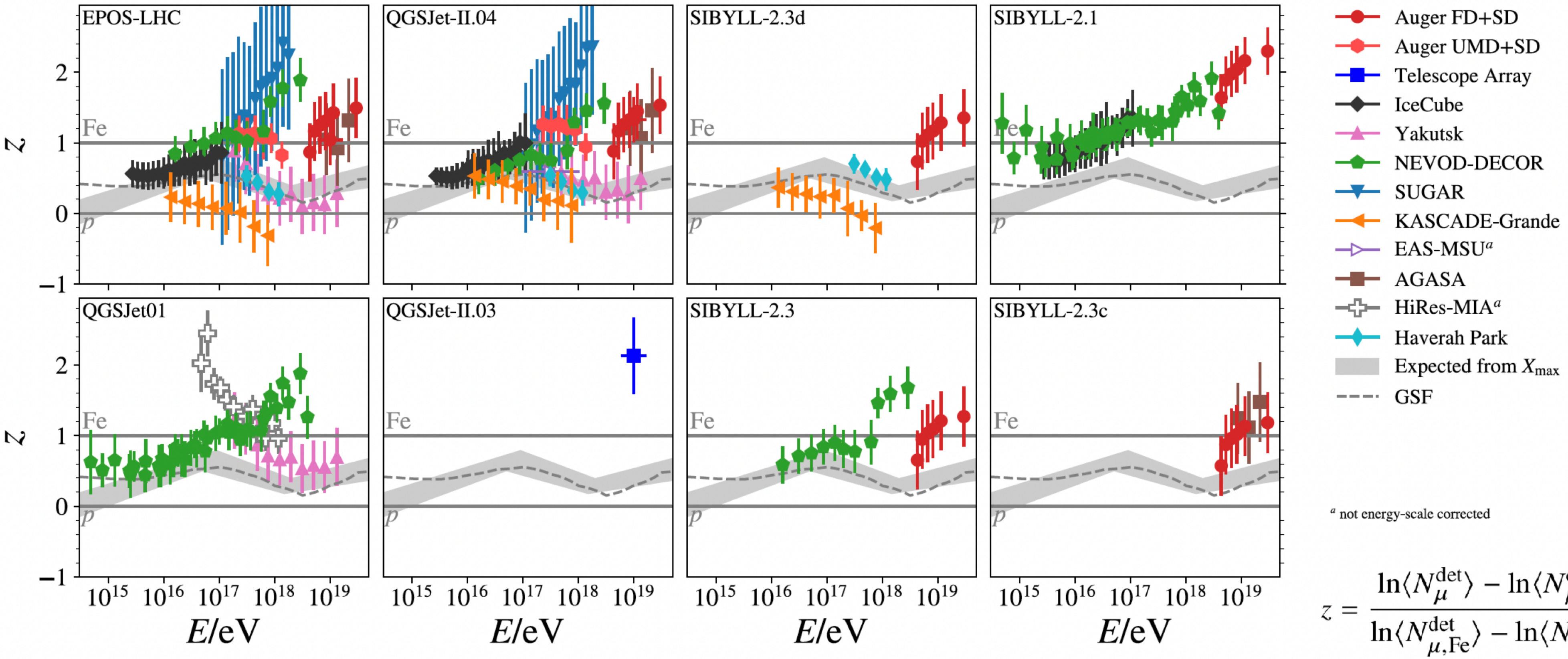
- ~1.5-3σ problem to describe the size of the muon content: **factor ~1.3-1.6** !
- problem seen at various energies and zenith angles

WHISP - energy evolution of the muon problem

[PoS(ICRC2023)466, L.Cazon Jan 2024 - Workshop on the Tuning of hadronic interactions]

- The z-scale after applying the energy shifts for common energy calibration.

Preliminary



$$z = \frac{\ln\langle N_{\mu}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

Observables relevant to hadronic interaction models

SD signal

- muon content
  - from buried scintillators, θ<45°
  - from N_{19}, θ>65°
- muon production depth
  - for core distance r > 1500m, θ>65°
- muon energy spectrum
  - from attenuation with θ and r
- rise time of signal vs. r

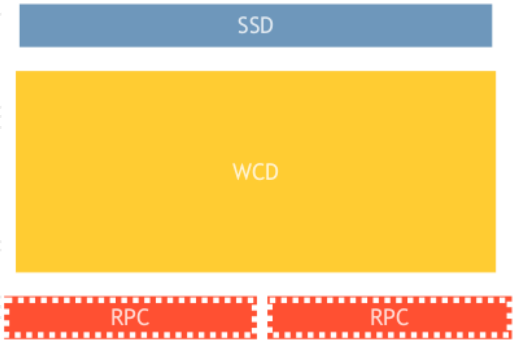
- very hard in general with SD only
- large systematics from energy scale

- multi-detector approach necessary:
  - SD+FD at different zenith angles
  - WCD+RPC+SSD+UMD+RD @ AugerPrime

FD longitudinal profile

- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A

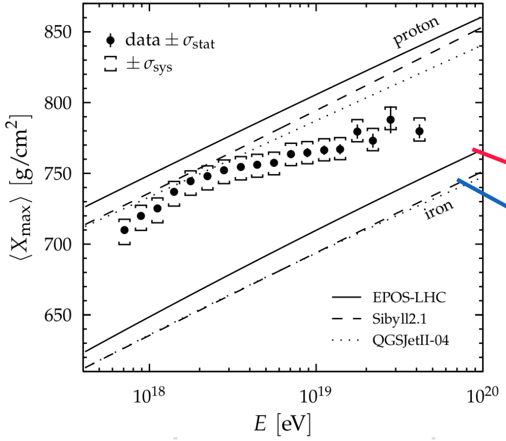
+ Radio Detector



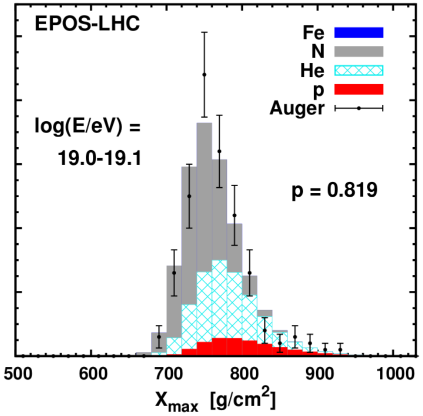
+ Underground Muon Detector

Observables relevant to hadronic interaction models

[Phys. Rev. D 90 (2014) 122005]

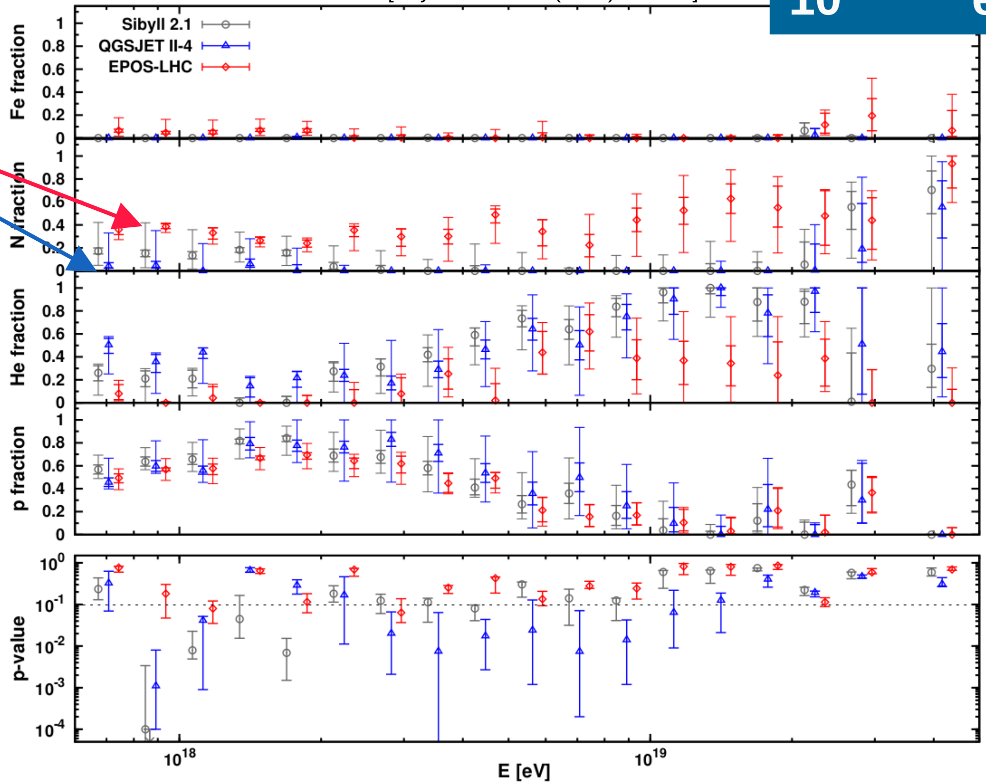


→ for core distance



[Phys. Rev. D 90 (2014) 122006]

$10^{17.8\text{-}19.6}$ eV



FD longitudinal profile

- estimation of primary masses from X_{max} fits

dependent on MC X_{max} scale
- input into many hadronic interaction studies

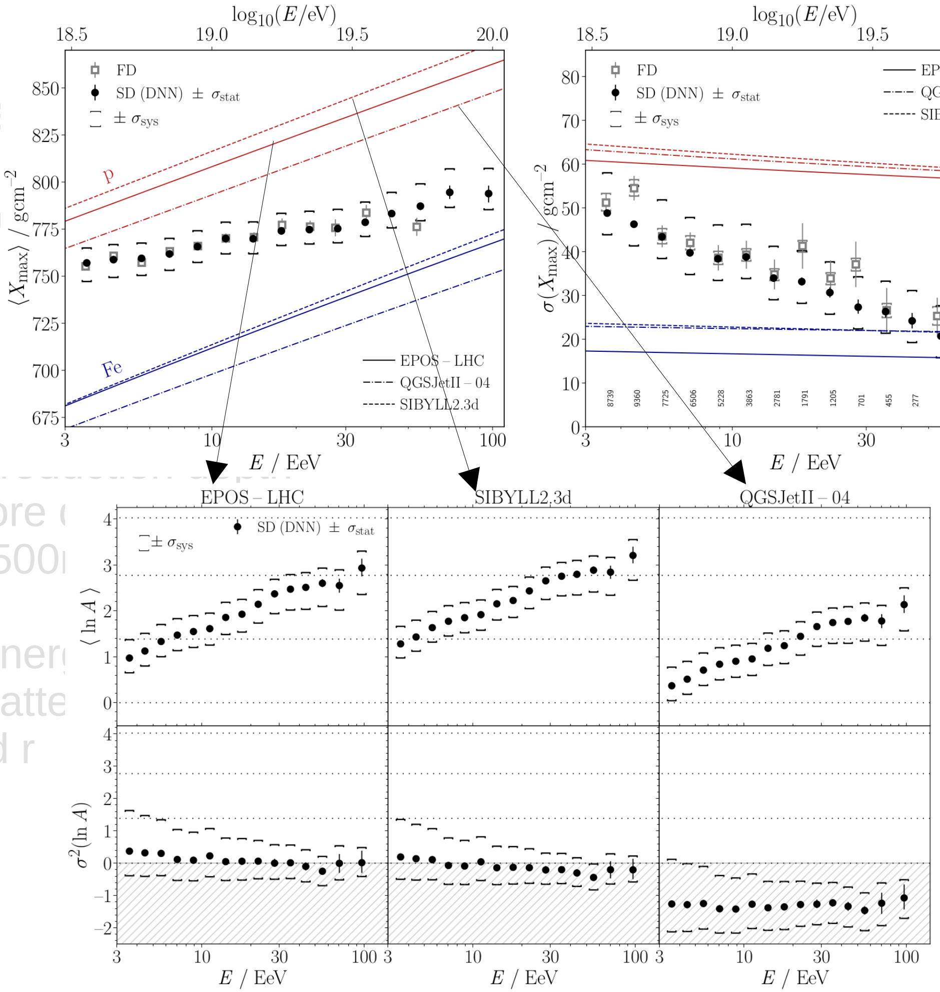
- average shape of longitudinal profiles
- frequency of anomalous showers

Observables relevant to hadronic interaction models

[accepted in PRD, arXiv:2406.06319]

SD signa

- muon c
  - from scinti
  - from
- muon p
  - for core r > 1500
- muon ener
  - from atte θ and r



Fe

O

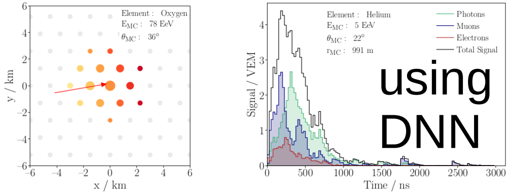
He

p

pure beam

$10^{18.5-20.0}$ eV

FD longitudinal profile



- interpretation of X_{max} moments using ln A

$$\langle \ln A\rangle = \frac{\langle X_{max}\rangle - \langle X_{max}\rangle_p}{f_E}$$

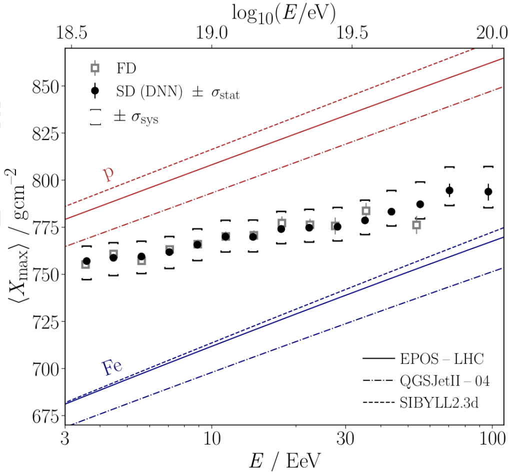
$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{max}) - \sigma^2_{sh}(\langle \ln A\rangle)}{b\,\sigma^2_p + f_E^2}$$

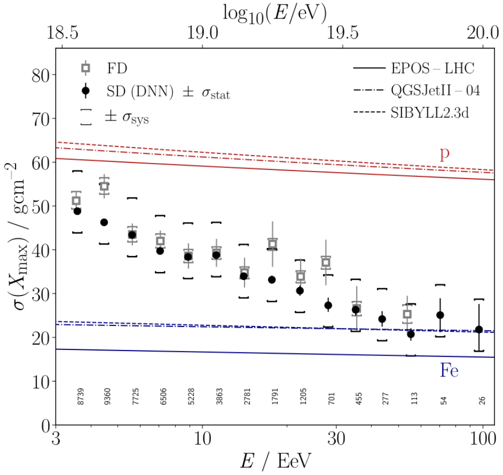
[JCAP 02 (2013) 026]

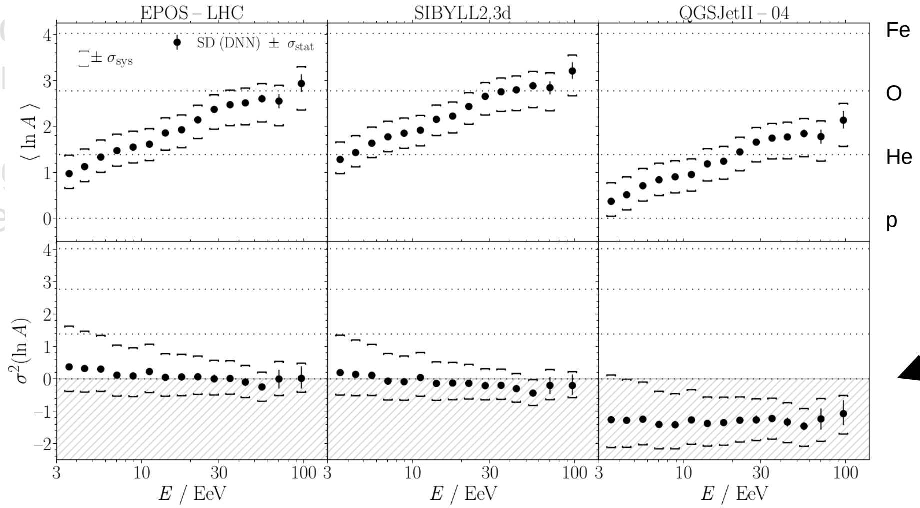
Strong dependance on the MC X_{max} scale

Observables relevant to hadronic interaction models

[accepted in PRD, arXiv:2406.06319]







$10^{18.5\text{-}20.0}$ eV

SD signa

- muon c
  - from
    scinti
  - from
- muon p
  - for core
    r > 1500
- muon ener
  - from atte
    θ and r

FD longitudinal profile

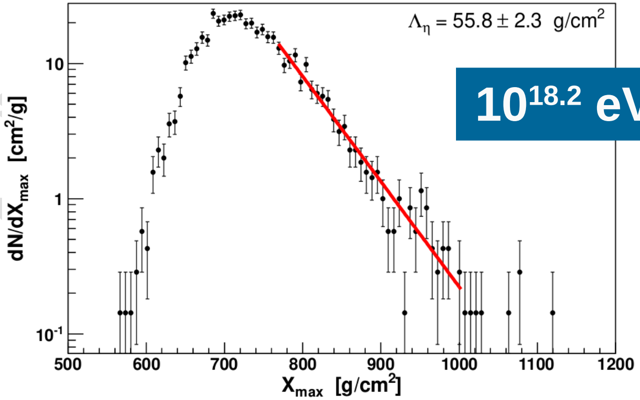
- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A
- p-air cross-section from tail of X_{max} distribution

Indication of too shallow predictions of $\langle X_{max} \rangle$ for all three models !

showers

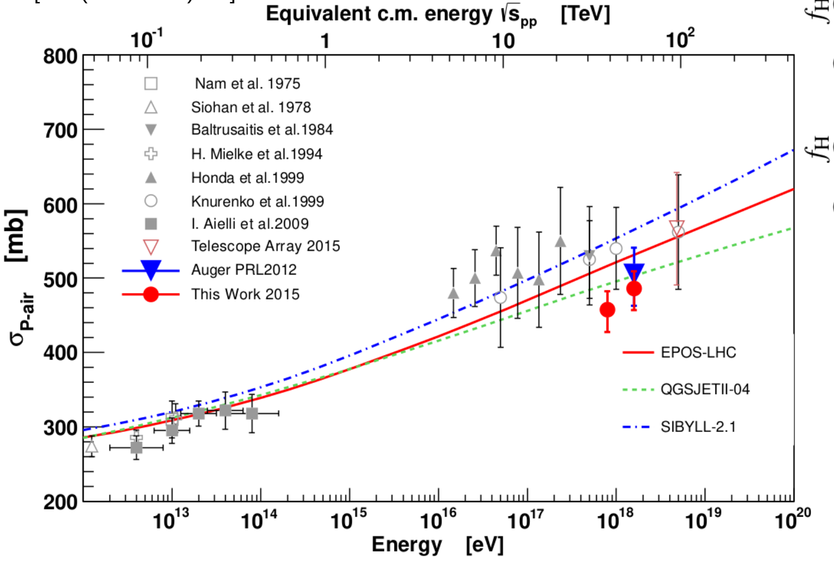
Observables relevant to hadronic interaction models

[Phys. Rev. Lett. 109 (2012) 062002]

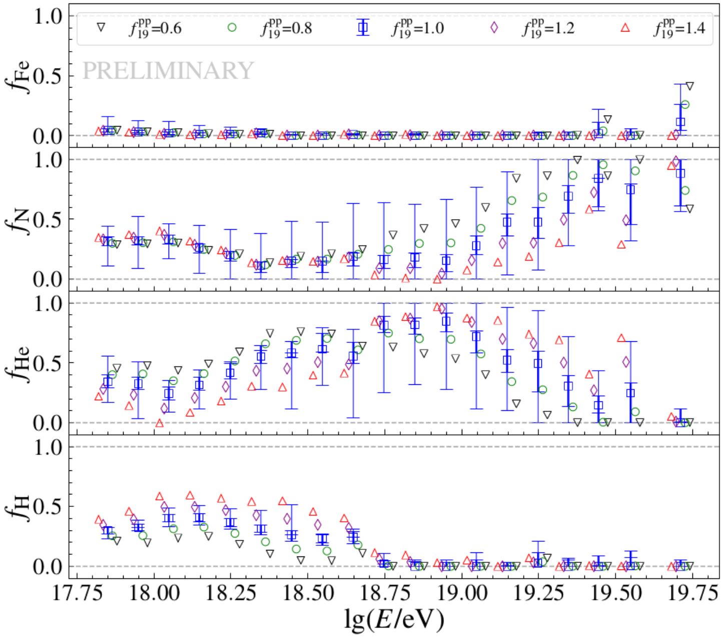


$10^{18.2}$ eV

[PoS(ICRC2015)401]

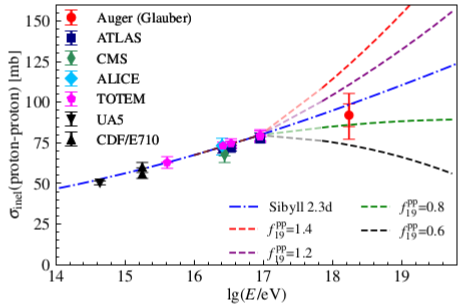


[O. Tkachenko for Pierre Auger Coll. PoS(ICRC2023)438]



$10^{17.7\text{-}19.8}$ eV ?

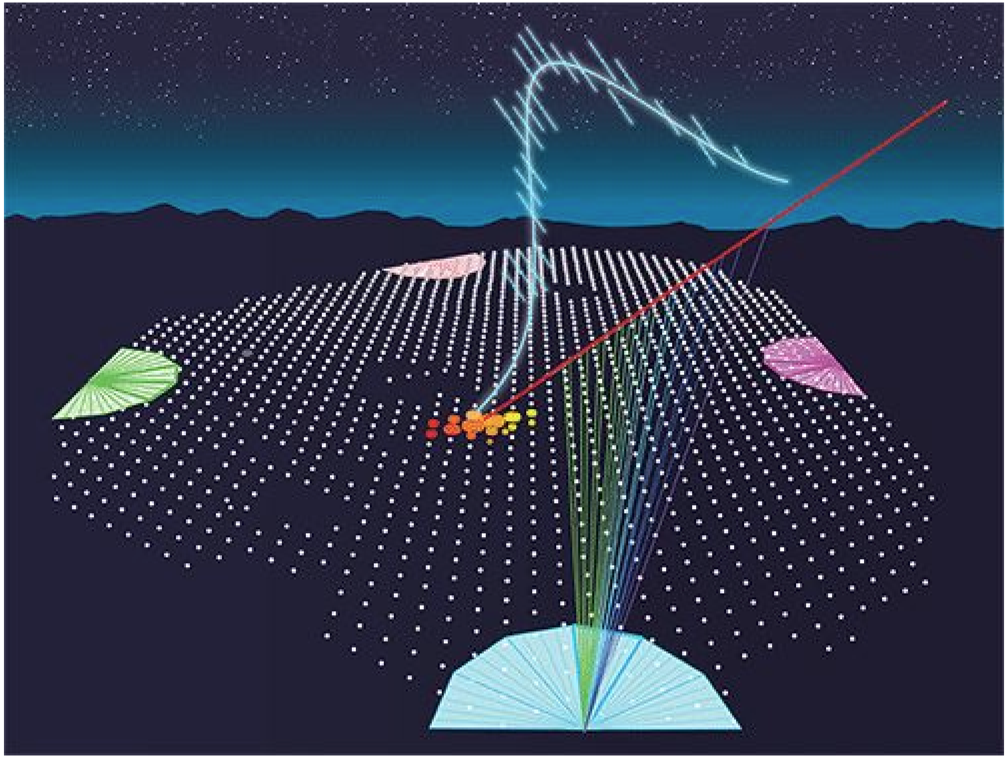
FD longitudinal profile



- p-air cross-section from tail of X_{max} distribution
- average shape of longitudinal profiles

- p-air cross-section consistent with current models
- new approach: composition+cross-section fit (decrease of systematics from He and X_{max} scale)

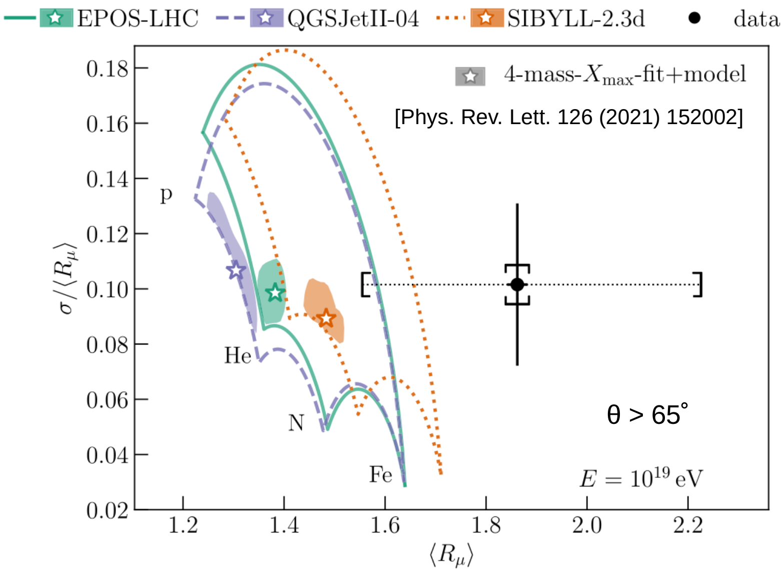
Combining SD and FD observables

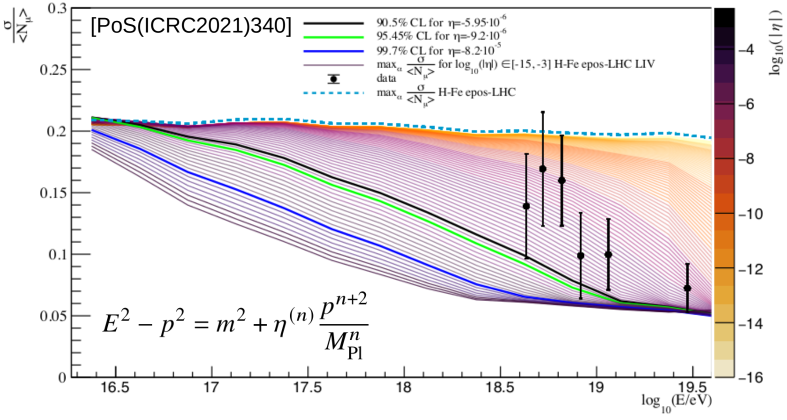


Ground signal + Longitudinal profile

- inclined showers + FD -> $\sigma(N_{\mu})$
- correlation between X_{max} and S(1000)
- top-down approach -> R_{had}
- applying shower-universality approach -> R_{had}
- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

Combining SD and FD observables





Ground signal + Longitudinal profile

- inclined showers + FD -> σ(N_μ) **~$10^{18.6\text{-}19.5}$ eV**
- correlation between X_{max} and S(1000)
- top-down approach -> R_{had}

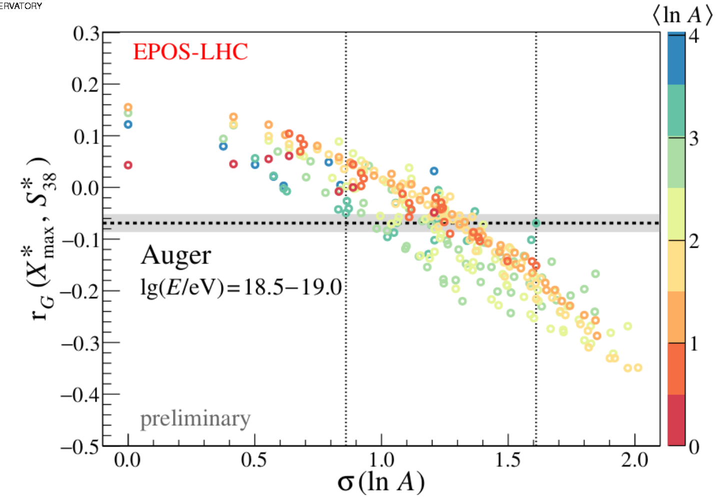
- confirmation of a problem to describe the size of the muon content: **factor ~1.3-1.6**
- muon fluctuations are consistent with data (no obvious problem in the first interaction)

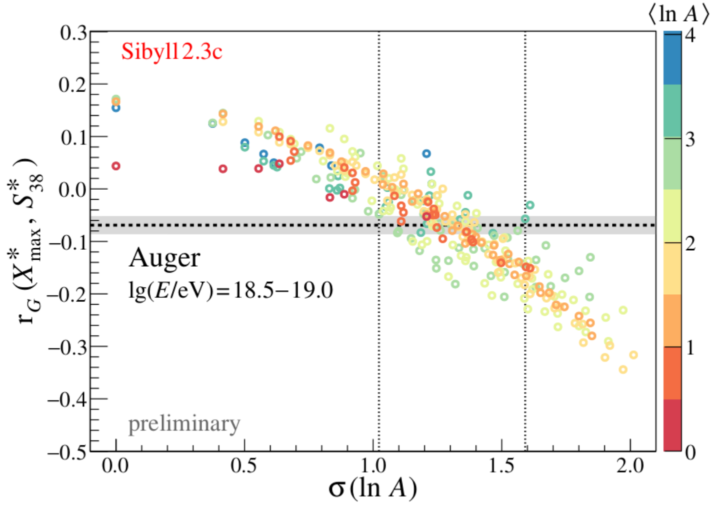
  ➔ strong constraints on the Lorentz invariance violation

  (journal publication in preparation)

Combining SD and FD observables

$10^{18.5\text{-}19.0}$ eV

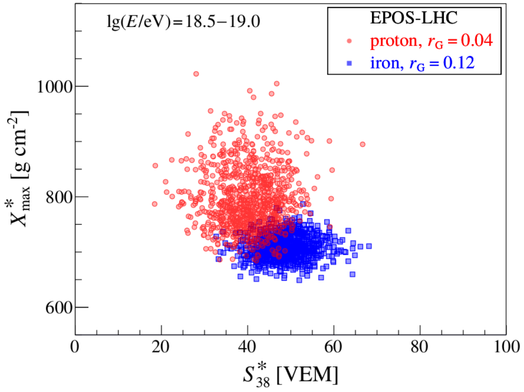




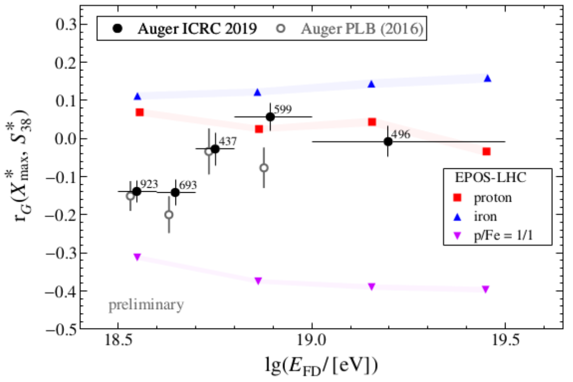
Ground signal + Longitudinal profile

- inclined showers + FD -> $\sigma(N_\mu)$
- correlation between X_{max} and S(1000)

[Phys. Lett. B 762 (2016) 288]

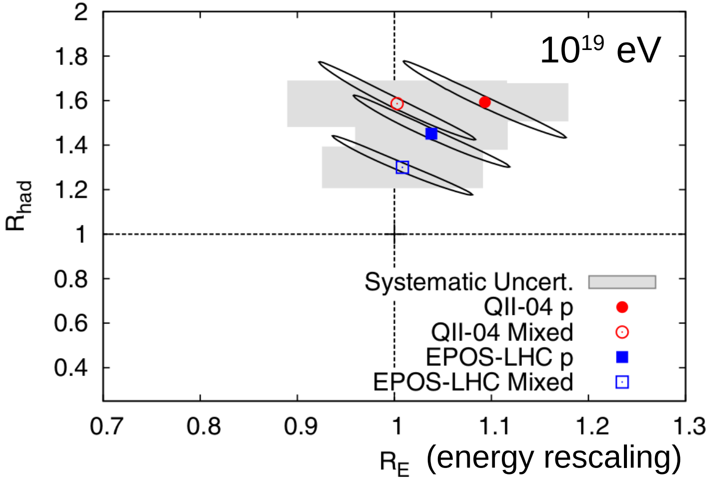


[A. Yushkov for Pierre Auger Coll.PoS(ICRC2019)482]

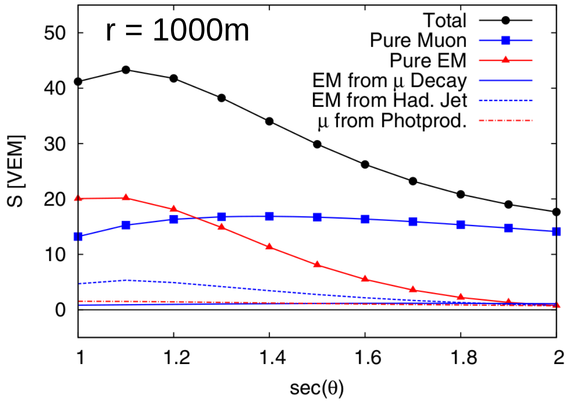


- ~model-independent estimator of spread of beam masses
- >5σ tension with light masses from X_{max} fits for QGSJet II-04 (**too shallow X_{max} scale**)

Combining SD and FD observables



$$S_{resc}(R_E, R_{had})_{i,j} \equiv R_E S_{EM,i,j} + R_{had} R_E^{\alpha} S_{had,i,j}$$



Ground signal + Longitudinal profile

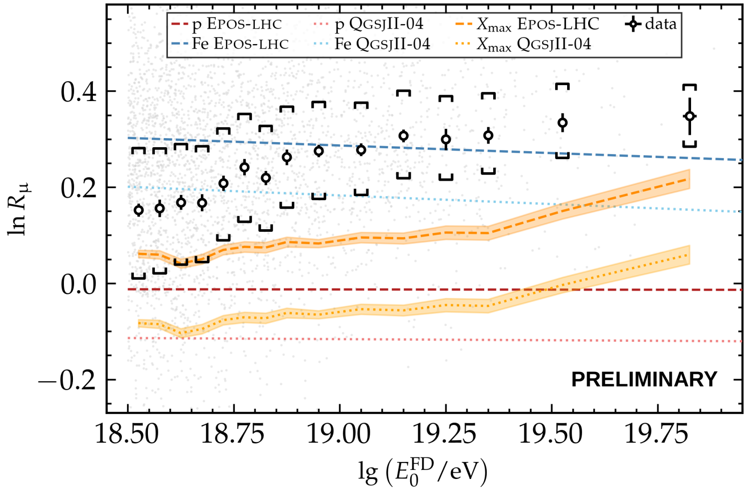
- inclined showers + FD -> $\sigma(N_\mu)$
- correlation between X_{max} and S(1000)
- top-down approach -> R_{had} **~ 1.3 - 1.6 !**

  [Phys. Rev. Lett. 117 (2016) 192001]
- applying shower-universality approach -> R_{had}
- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

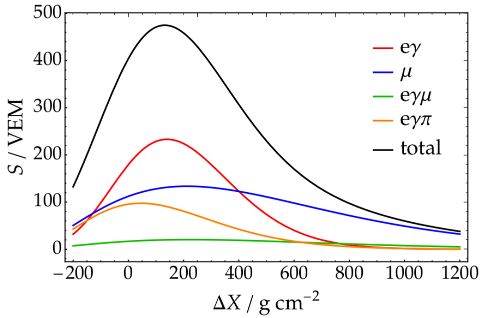
- mass from measured X_{max} - depends on MC X_{max} scale
- ~2-3σ tension with strong dependence on energy scale

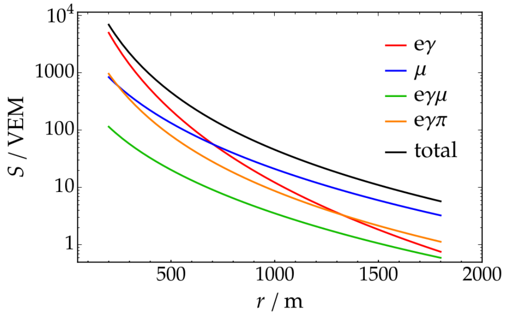
Combining SD and FD observables

shower geometry, energy and X_{max} from FD

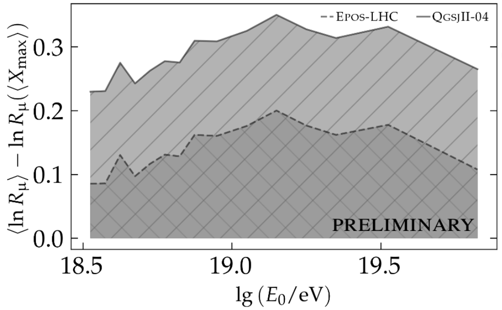


$$S_{tot} \simeq S_{e\gamma} + R_\mu \left(S_\mu + S_{e\gamma(\mu)} + S_{e\gamma(\pi)}\right)$$





Ground signal + Longitudinal profile



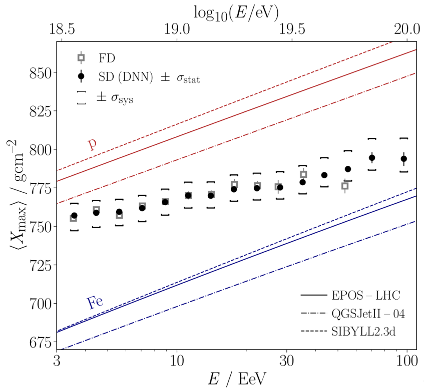
$10^{18.5-19.8}$ eV

- applying shower-universality approach -> R_{had} **~ 1.1 - 1.3** [PoS(ICRC2023)339, arXiv:2405.03494]
- 2-dim distributions [S(1000), X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

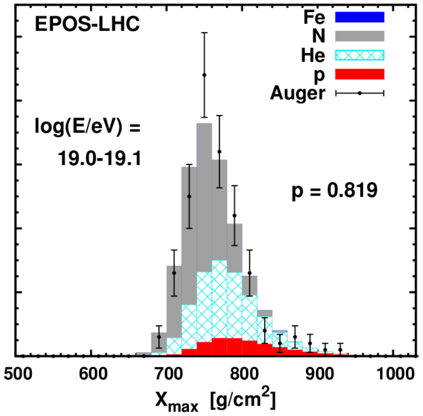
- ~2σ tension
- R_{had} smaller than in top-down approach
- ~insensitive to the MC X_{max} scale
- journal publication in preparation

Mass composition & tests of hadronic interactions

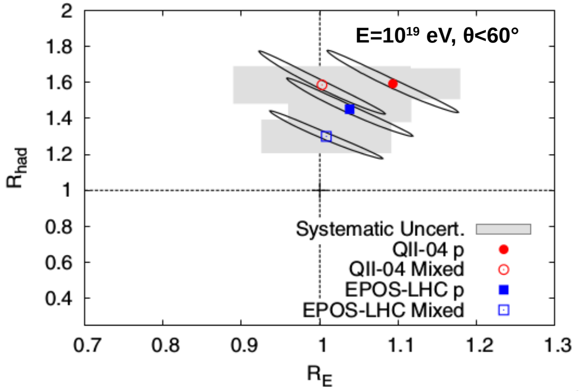
[accepted in PRD, arXiv:2406.06319]



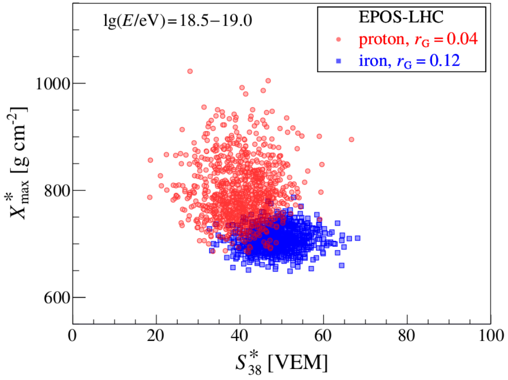
[Phys. Rev. D 90 (2014) 122006]



[Phys. Rev. Lett. 117 (2016) 192001]



[Phys. Lett. B 762 (2016) 288]



MC X_{max} scale ?

Primary fraction fit

Deficit in MC hadronic signal

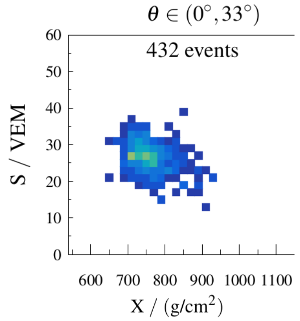
~ model-independent estimation of beam mixing from [X_{max},S(1000)] correlation

MC:

$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

[Phys. Rev. D 109 (2024) 102001]



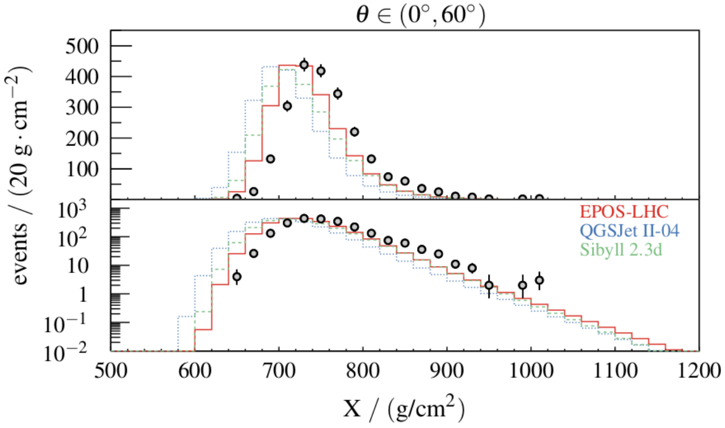
Mass composition fit of observed [X_{max},S(1000)](θ) distributions with free modification of MC predictions **not only of hadronic signal but also of X_{max}**

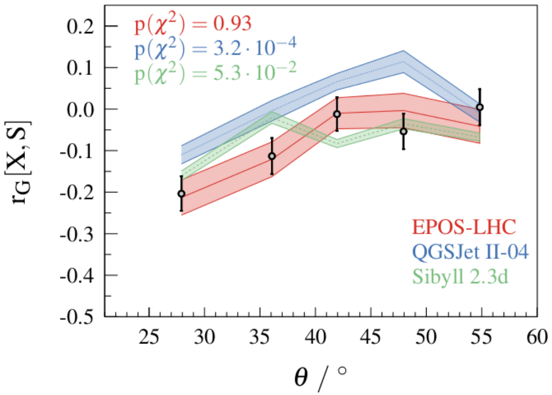
Improvement in data description

PIERRE AUGER OBSERVATORY

$10^{18.5\text{-}19.0}$ eV

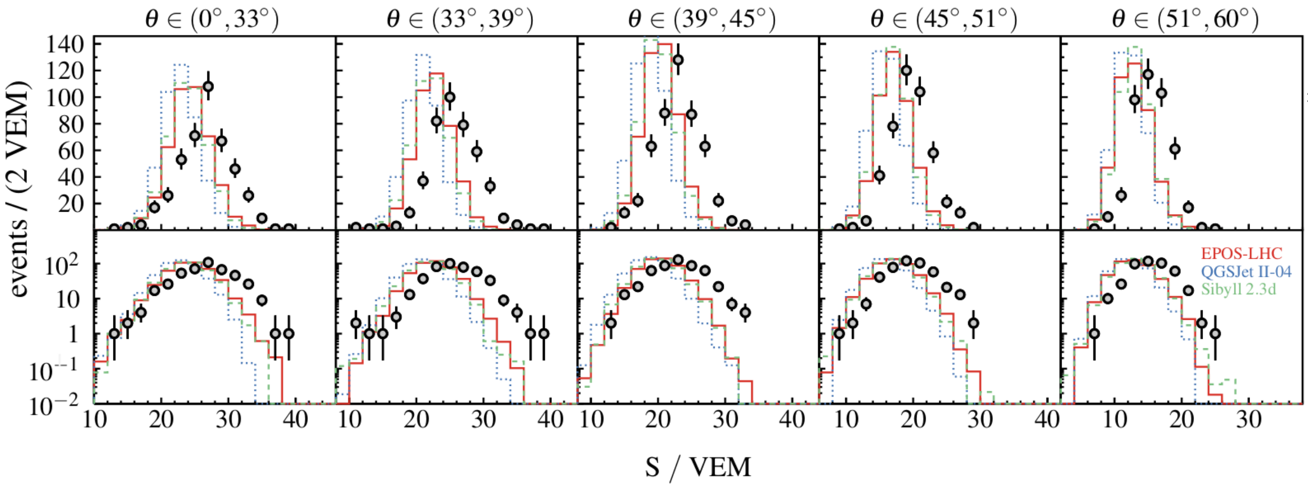
[Phys. Rev. D 109 (2024) 102001]





$$\ln \mathscr{L} = \begin{cases} \sum_k \sum_j (C_{jk} - n_{jk} + n_{jk} \ln \frac{n_{jk}}{C_{jk}}), & n_{jk} > 0 \\ \sum_k \sum_j C_{jk}, & n_{jk} = 0 \end{cases}$$

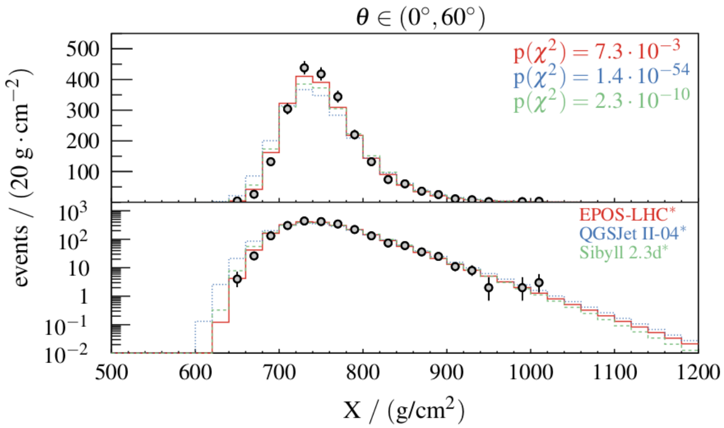
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
none	2022.9	4508.0	2496.5
ΔX_{max}	738.6	1674.8	1015.7
R_{had} = const.	489.2	684.4	521.6
$R_{had}(\theta)$	489.2	673.9	517.6
R_{had} = const. and ΔX_{max}	452.2	486.7	454.2
$R_{had}(\theta)$ and ΔX_{max}	451.9	476.3	451.6

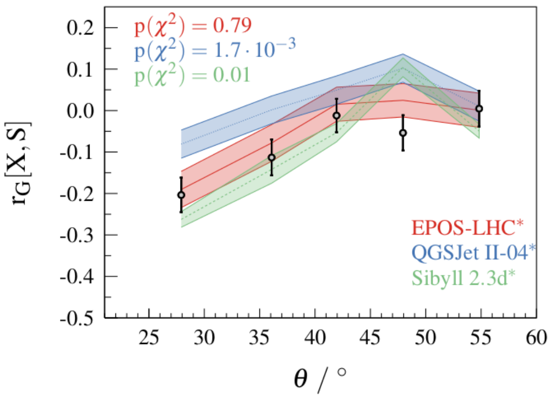


Improvement in data description

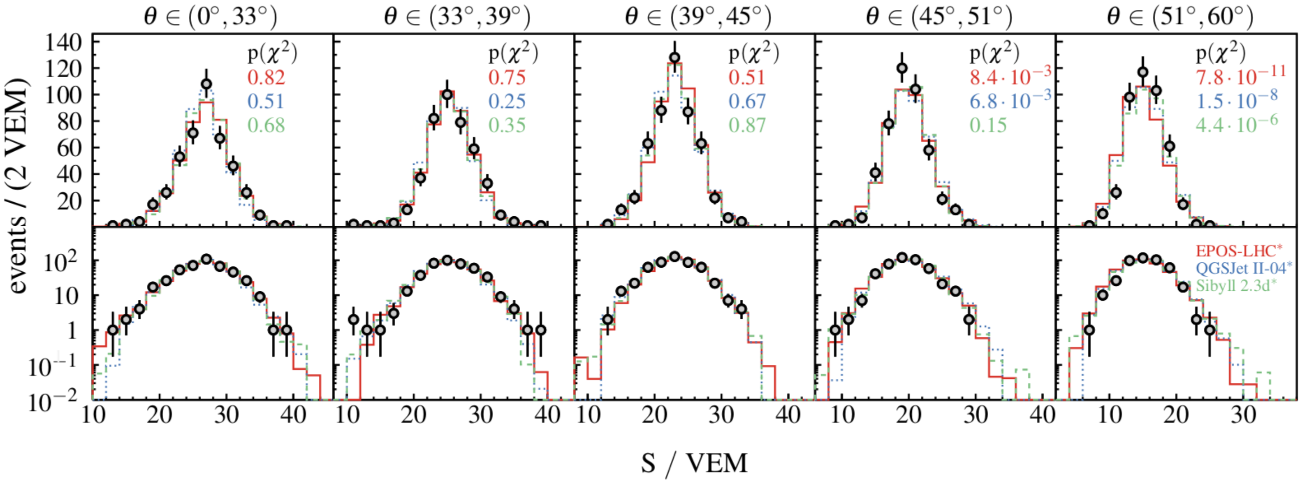
$10^{18.5\text{-}19.0}$ eV

[Phys. Rev. D 109 (2024) 102001]





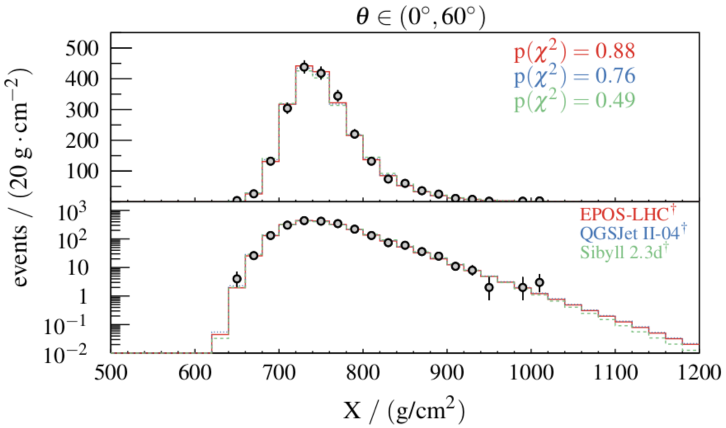
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
none	2022.9	4508.0	2496.5
ΔX_{max}	738.6	1674.8	1015.7
R_{had} = const.	489.2	684.4	521.6
$R_{had}(\theta)$	489.2	673.9	517.6
R_{had} = const. and ΔX_{max}	452.2	486.7	454.2
$R_{had}(\theta)$ and ΔX_{max}	451.9	476.3	451.6

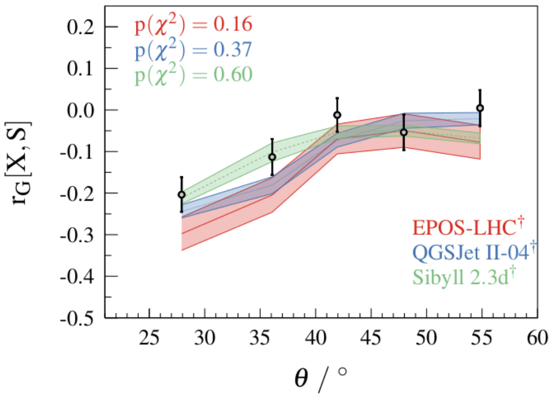


Improvement in data description

$10^{18.5\text{-}19.0}$ eV

[Phys. Rev. D 109 (2024) 102001]





p-values of fits from MC-MC tests > 10% for all three models

$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
none	2022.9	4508.0	2496.5
ΔX_{max}	738.6	1674.8	1015.7
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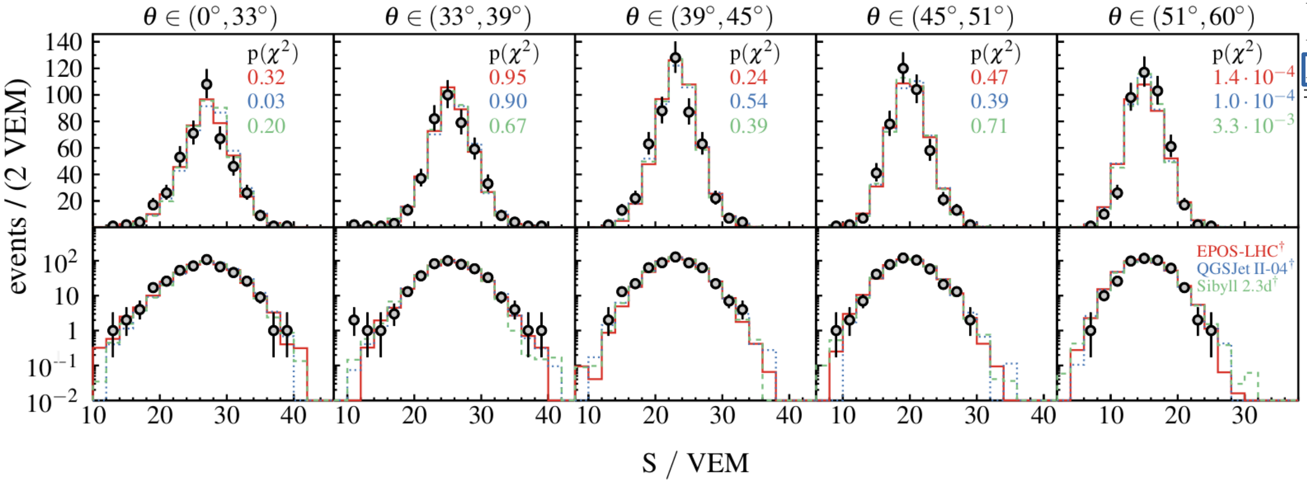


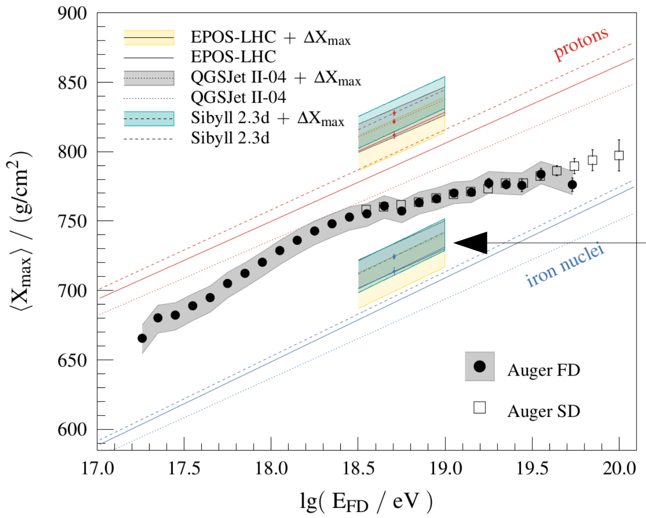
Significant improvement >5σ using R_{had} and ΔX_{max} (Likelihood ratio tests for nested model using Wilks' theorem)

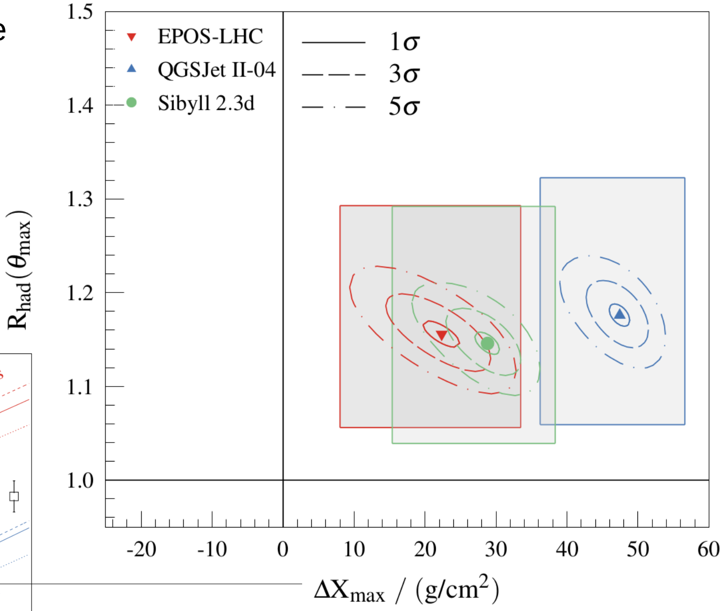
Fitted parameters

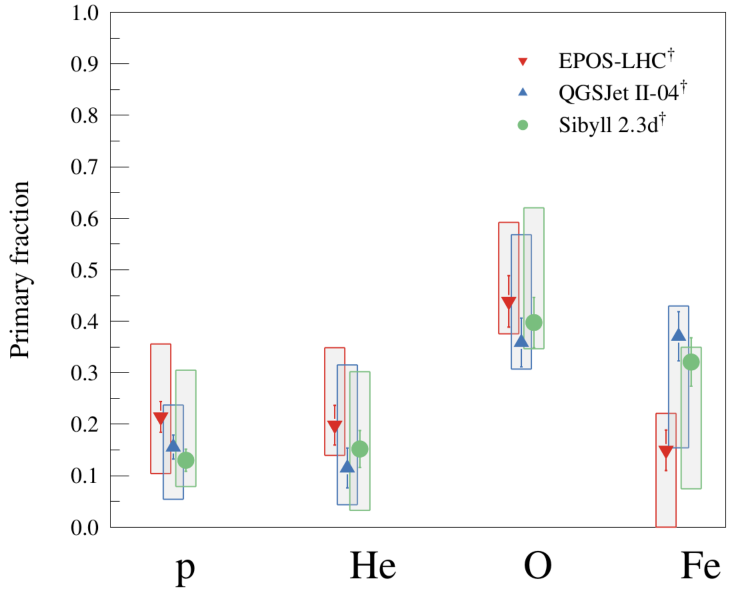
$10^{18.5\text{-}19.0}$ eV

[Phys. Rev. D 109 (2024) 102001]

Zenith dependence of R_{had} assumed to be linear in X_{ground}-X_{max}
→ $R_{had}(\theta_{min}$~28°), $R_{had}(\theta_{max}$~55°)





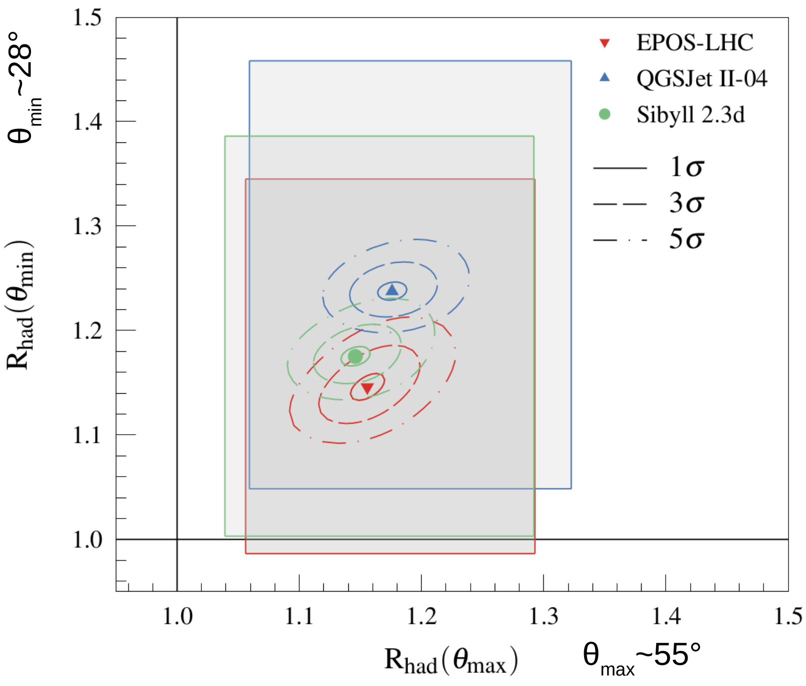


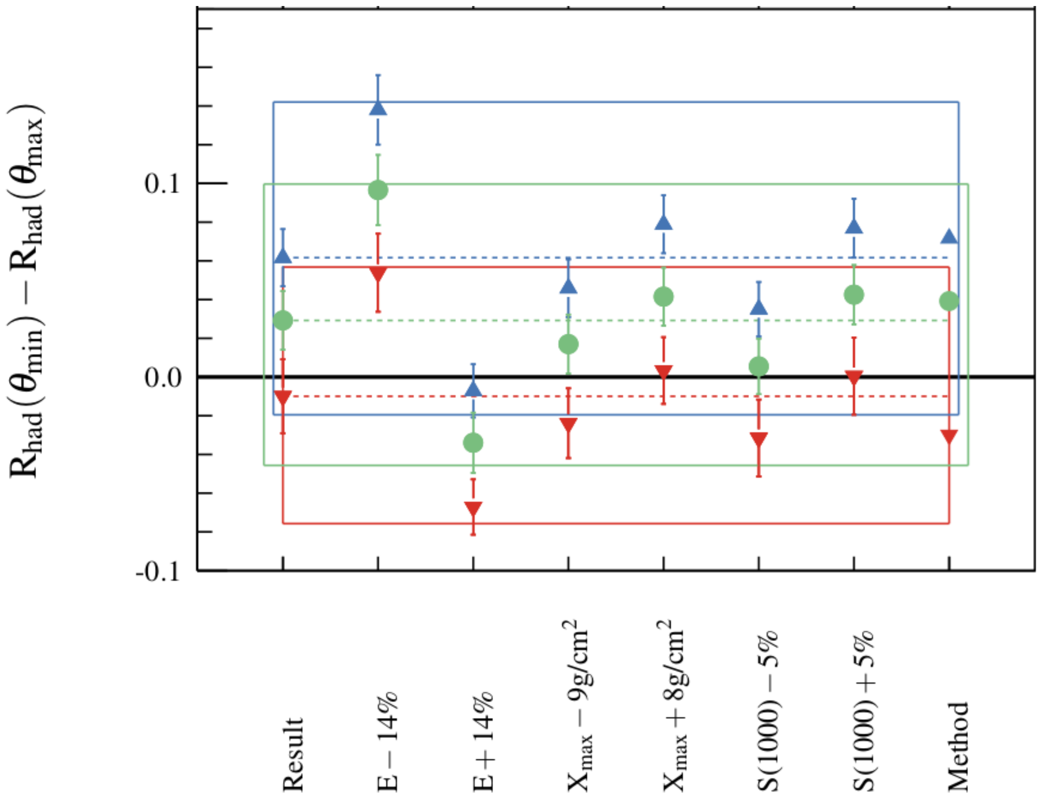
- **deeper X_{max} predictions for all models !**
- alleviated "muon problem" to ~15-25%
- smaller model differences in mass composition

Attenuation of hadronic signal with zenith angle

[Phys. Rev. D 109 (2024) 102001]

$10^{18.5\text{-}19.0}$ eV



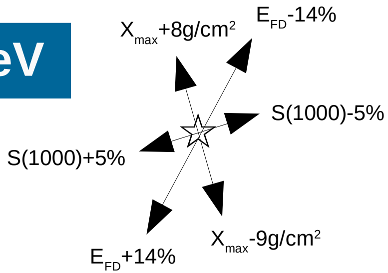


Indication of harder muon spectra in QGSJet II-04 than in data

Scanning in combinations of experimental systematics

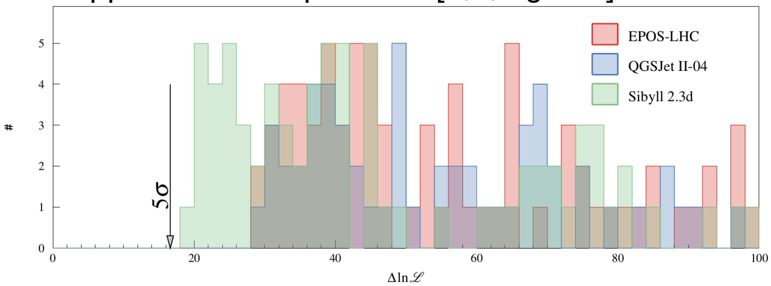
[Phys. Rev. D 109 (2024) 102001]

$10^{18.5\text{-}19.0}$ eV

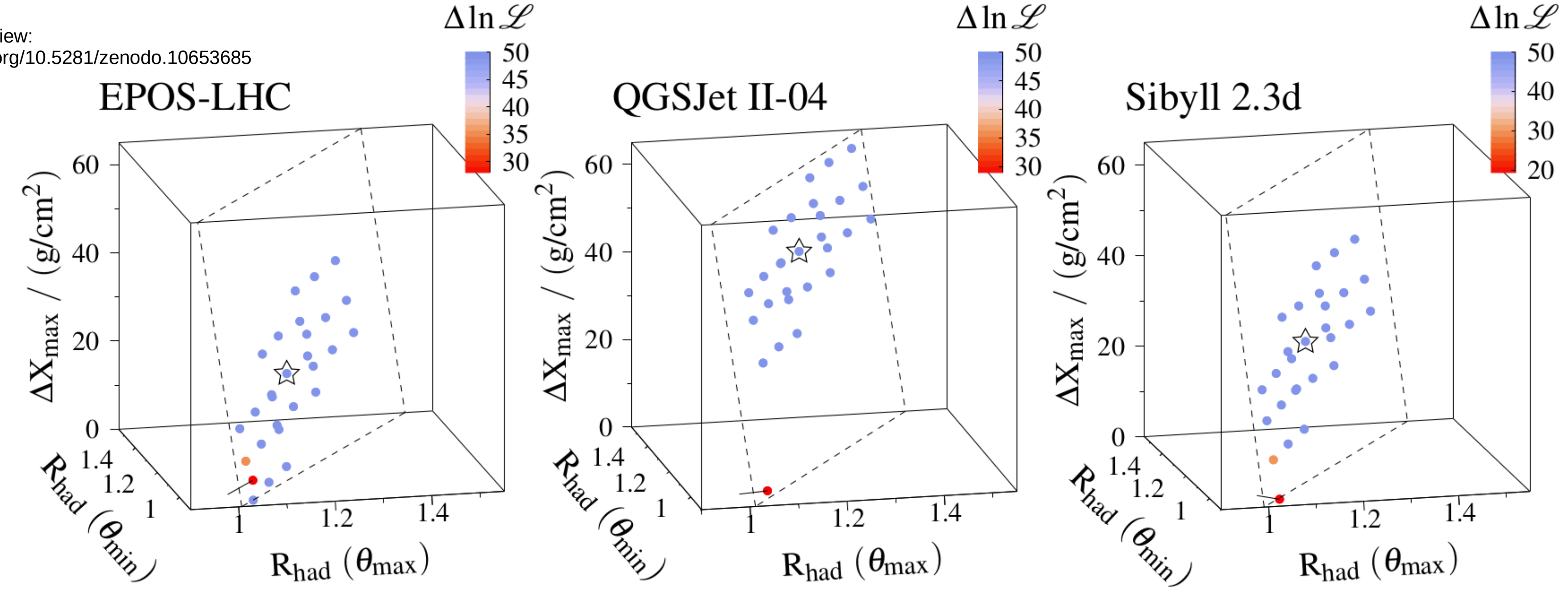


Significance of improvement of data description always above 5σ

Denser scan in the region of the closest approach of the plane to [1,1,0 g/cm^2]



Animated view:
https://doi.org/10.5281/zenodo.10653685



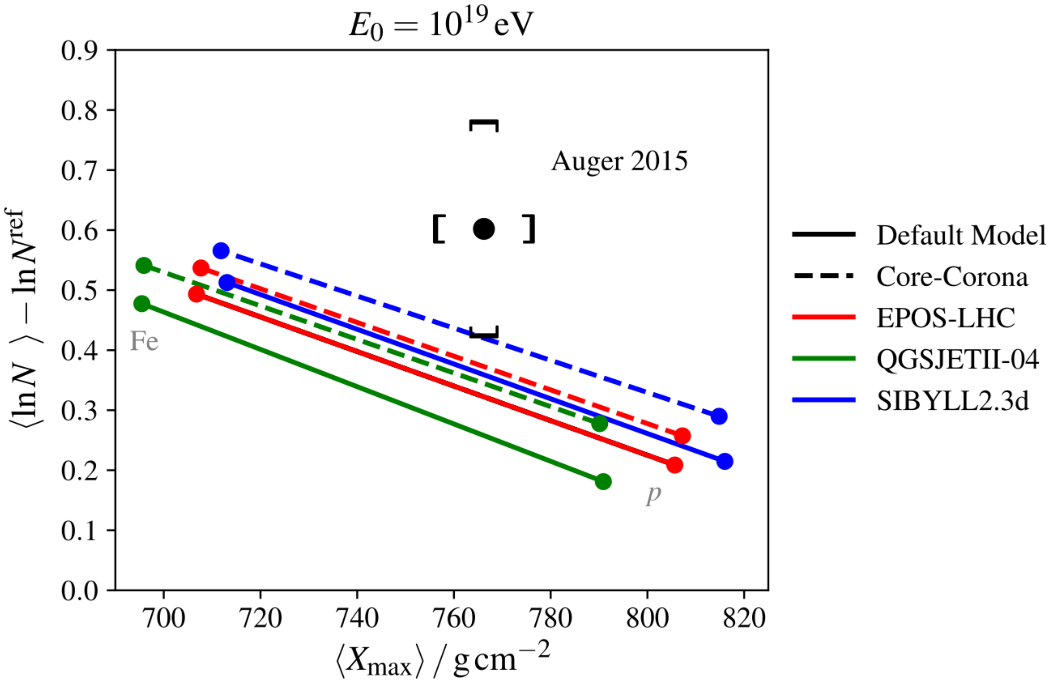
Summary of tests of models using Auger data

test	energy / EeV	θ / °	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
X_{max} moments	~3 to 50	0 to 80	no tension	tension	no tension (2.3c)
X_{max}:$S(1000)$ correlation	3 to 10	0 to 60	no tension	tension	no tension (2.3c)
mean muon number	~10	~67	tension	tension	tension
mean muon number	0.2 to 2	0 to 45	tension	tension	—
fluctuation of muon number	4 to 40	~67	no tension	no tension	no tension
muon production depth	20 to 70	~60	tension	no tension	—
$S(1000)$	~10	0 to 60	tension	tension	—
[X_{max}, S(1000)] fits	3 to 10	0 to 60	tension	tension	tension

- all models have problems ...
- a need to describe consistently both X_{max} and ground signal - issue in both observables !

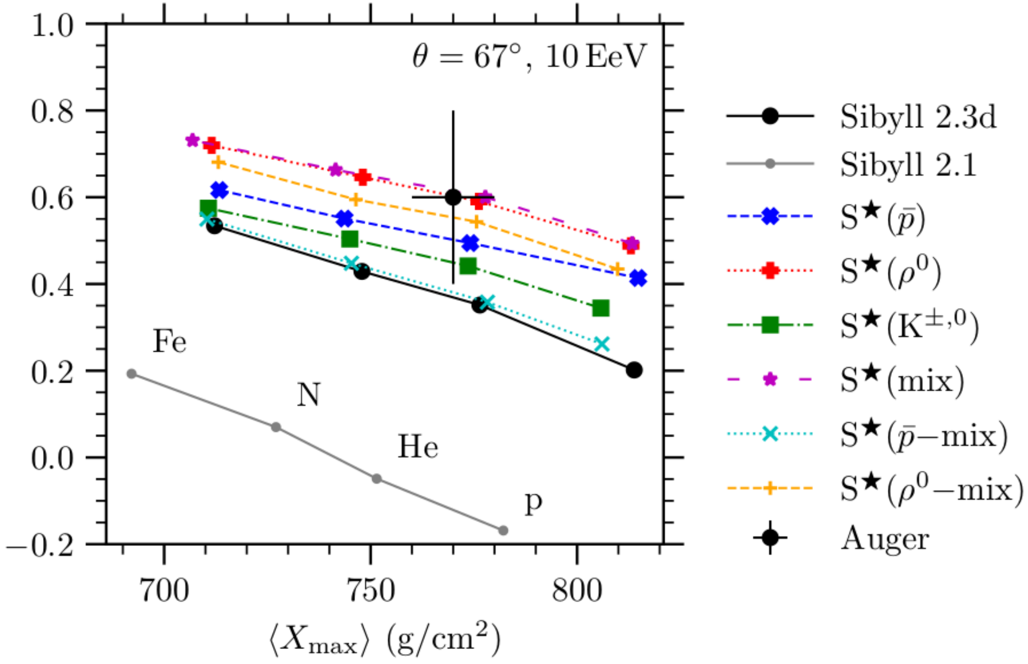
Adding muons ~ without changing X_{max}

Core-corona model - collective statistical hadronization ➔ EPOS 4



[Phys. Rev. D 107 (2023) 094031]

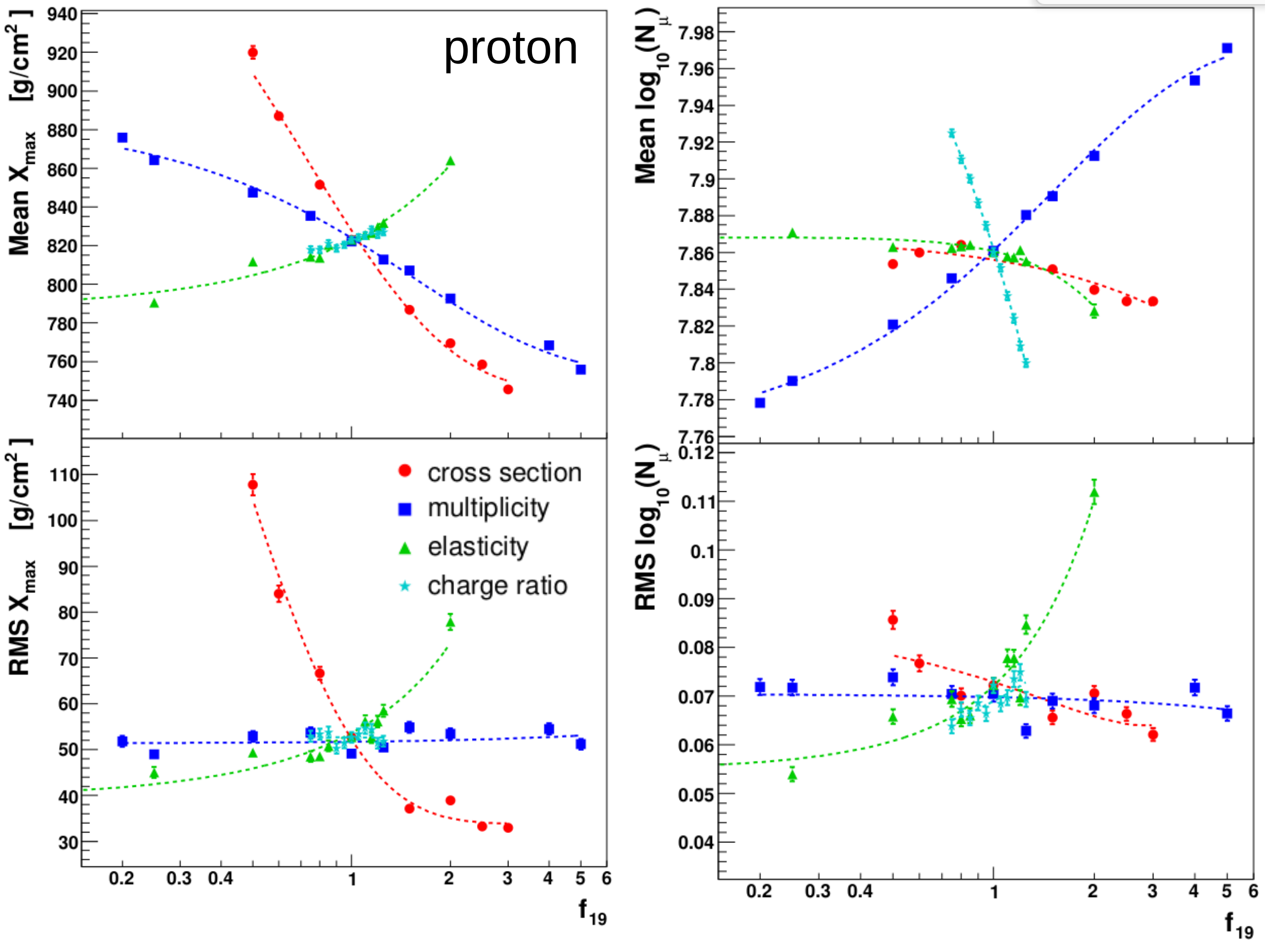
Sibyll * - artificial enhancement of muons



[PoS(ICRC2023)429]

Modifications of hadronic interactions

- 1D CONEX simulations
- Sibyll 2.1 @ $10^{19.5}$ eV
- cross-section modification, or resampling of produced particles
- energy threshold for modifications 10^{15} eV



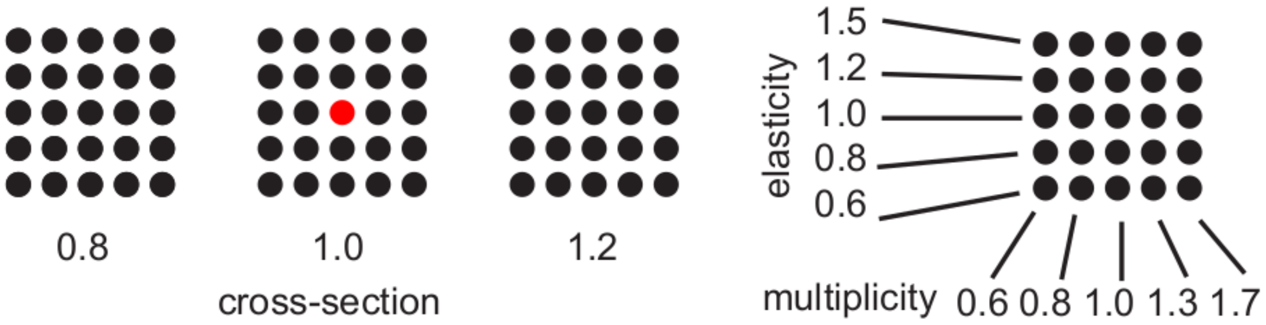
[Phys. Rev. D 83 (2011) 054026]

Towards more complex explanation: MOCHI

***MO**dified **C**haracteristics of **H**adronic **I**nteractions*

J. Ebr, JV, J. Blažek, T. Pierog, E. Santos, P. Travnicek, N. Denner and R. Ulrich [PoS(ICRC2023)245]

- CONEX in CORSIKA: 3D information
- modification factors in **cross-section**, **multiplicity** and **elasticity**



- **MOCHI library**:
  - Sibyll 2.3d
  - energy $10^{18.7}$ eV
  - protons and iron nuclei
  - 5 zenith angles
  - 1000 showers per „bin“
  - 750 000 showers (~200 TB, ~250y CPU time)

Range of modifications and thresholds

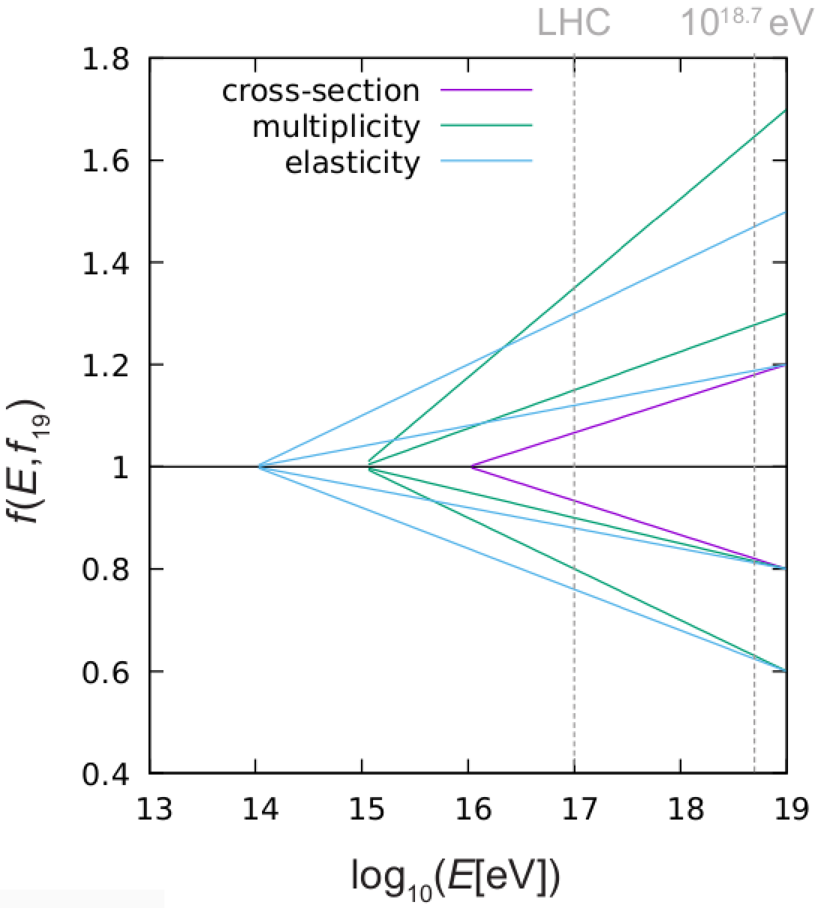
J. Ebr, JV, J. Blažek, T. Pierog, E. Santos, P. Travnicek, N. Denner and R. Ulrich [PoS(ICRC2023)245]

Cross-section ($E_{thr} = 10^{16}$ eV)
- well constrained for p-p at LHC to a few %
- unc. in conversion to p-A limited by CMS p-Pb measurement

Multiplicity ($E_{thr} = 10^{15}$ eV)
- no p-A data, limited rapidity coverage

Elasticity ($E_{thr} = 10^{14}$ eV)
- difficult at accelerators, limits from nuclear emulsion chambers
- recent LHCf neutron elasticity measurement?
- range of modifications limited by internal consistency

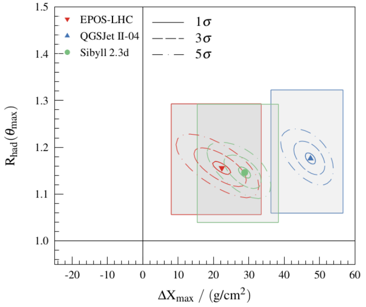
$$f(E, f_{19}) = 1 + (f_{19} - 1) \cdot \frac{\log_{10}(E/E_{\mathrm{thr}})}{\log_{10}(10\ \mathrm{EeV}/E_{\mathrm{thr}})}$$

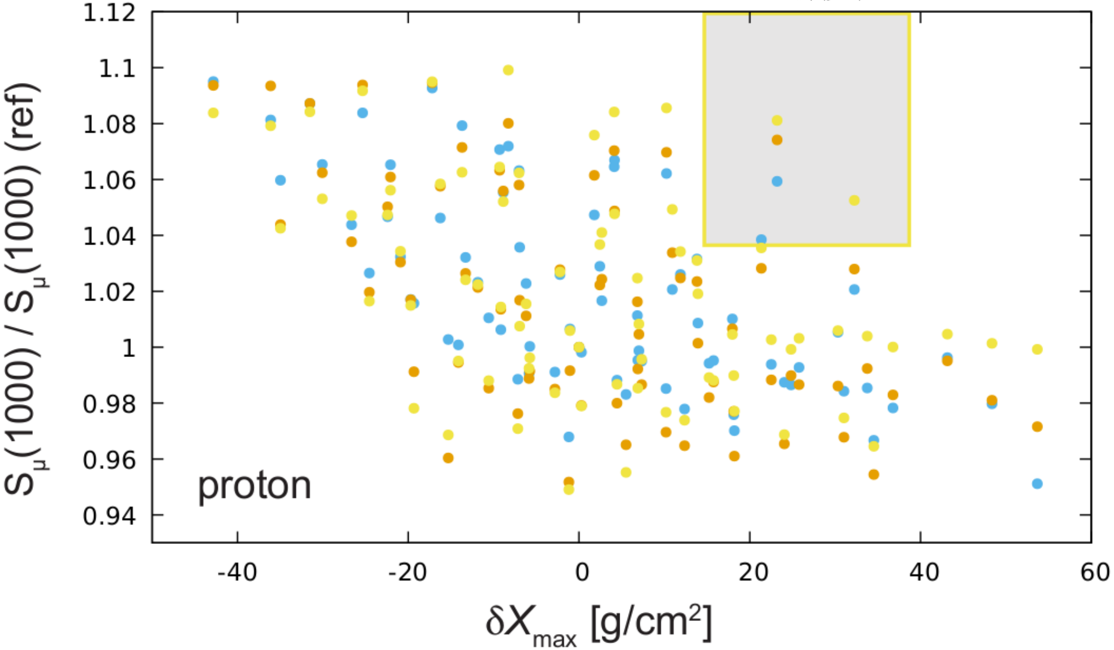


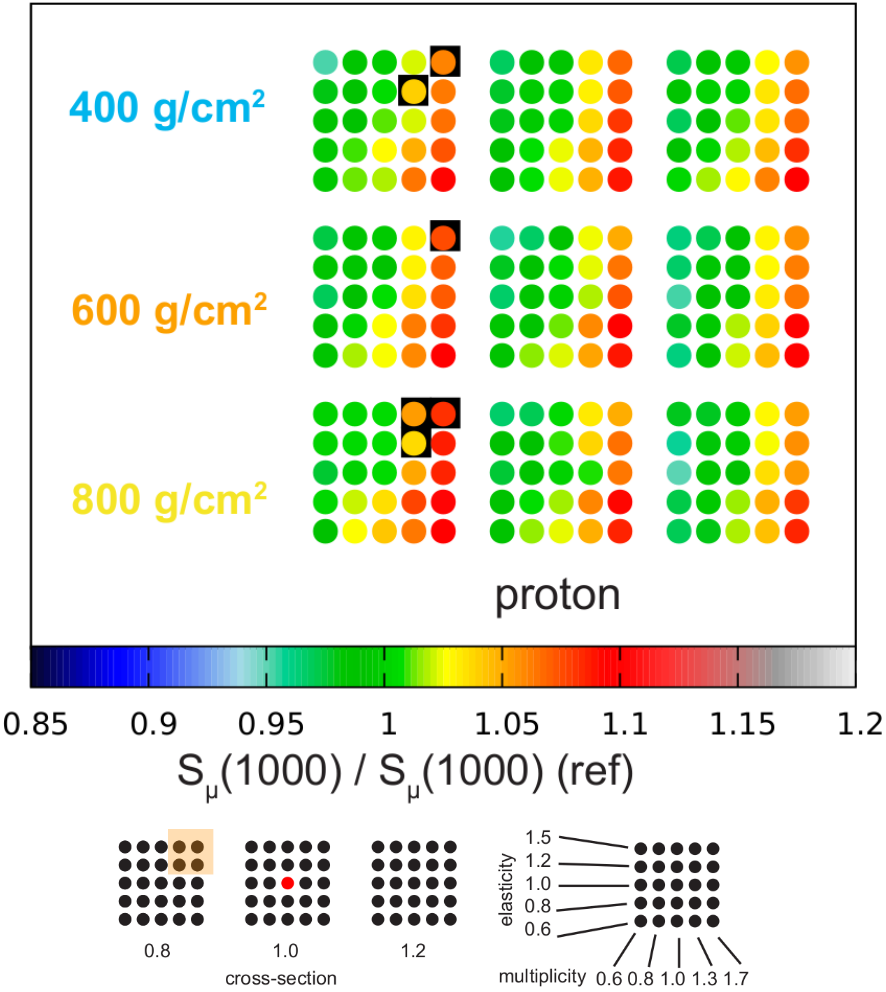
Comparison with Auger results

J. Ebr, JV, J. Blažek, T. Pierog, E. Santos, P. Travnicek, N. Denner and R. Ulrich [PoS(ICRC2023)245]

[Phys. Rev. D 109 (2024) 102001]

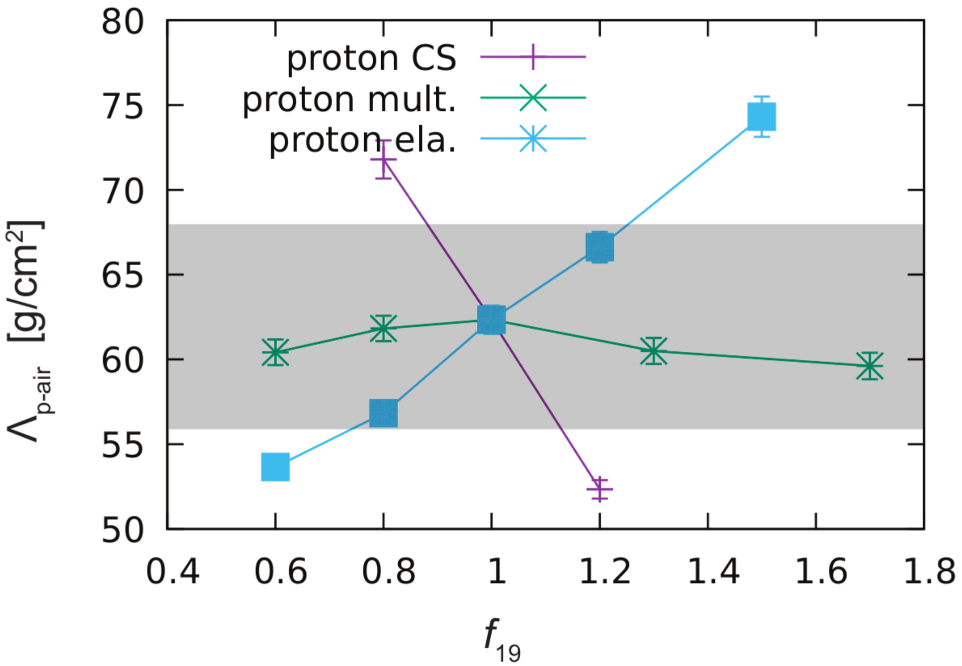


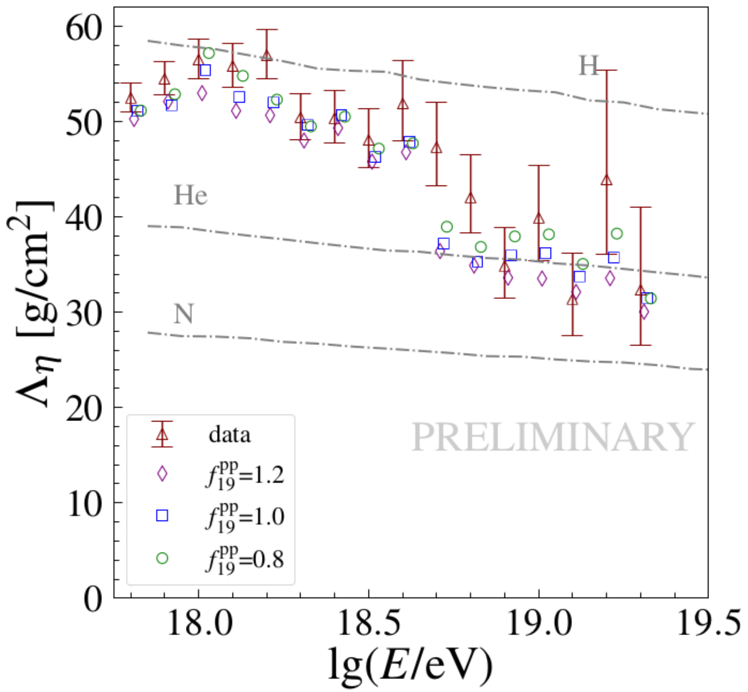


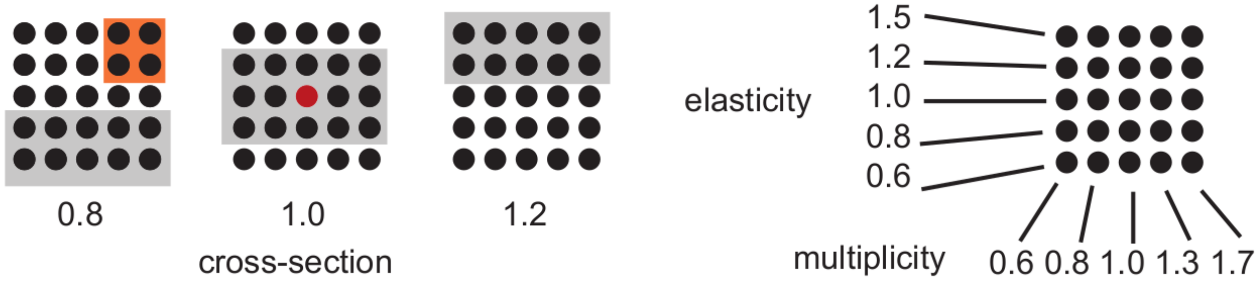


Effect on tail of X_{max} distribution

J. Ebr, JV, J. Blažek, T. Pierog, E. Santos, P. Travnicek, N. Denner and R. Ulrich [PoS(ICRC2023)245]



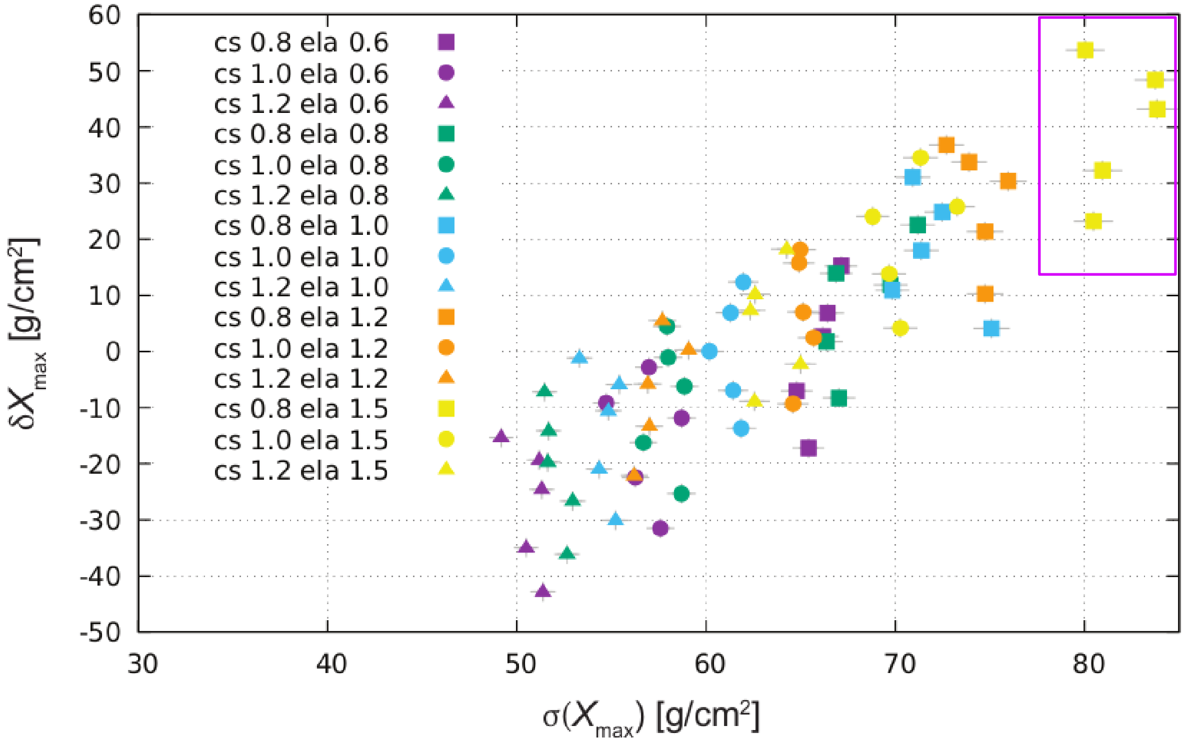




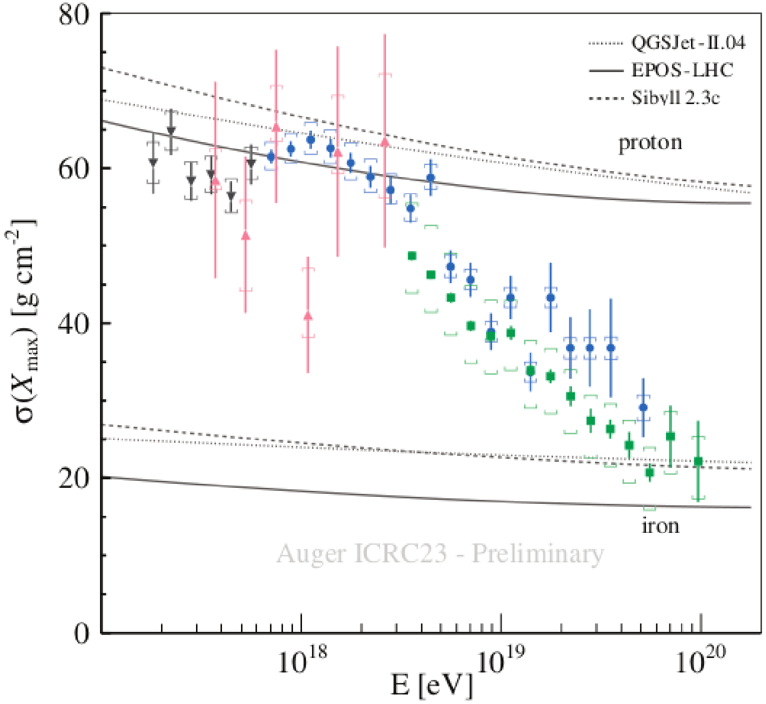
Slope of X_{max} tail distribution for protons too constrained by Auger data

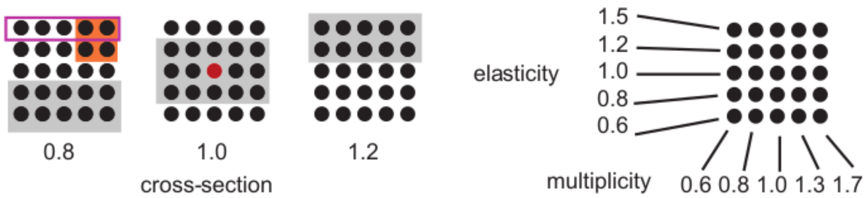
Effect on X_{max} fluctuations

J. Ebr, JV, J. Blažek, T. Pierog, E. Santos, P. Travnicek, N. Denner and R. Ulrich [PoS(ICRC2023)245]



PoS(ICRC2023)365





Lower cross-section and high elasticity leads to very high X_{max} fluctuations that may be difficult to reconcile with data

Summary on tests of models of hadronic interactions

- ~2-3σ data/MC tensions in many analyses, but some experiments are consistent

  ➔ systematics on energy estimation is crucial ➔ **multi-detector measurements needed** and cross-calibration methods seems to be esential !

- yet, it does not seem to be a solution ➔ **connections of low and high energy tests** of model predictions are crucial for understanding the systematic uncertainties on mass composition coming from shower modelling

- news from Auger at 3-10 EeV: **current models of hadronic interactions are proven to fail** to describe combined FD+SD data with **more than 5σ** !
  - possible underestimation of experimental systematics ruled out
  - possibility of a heavier mass composition (disappointing scenario) should be seriously considered !

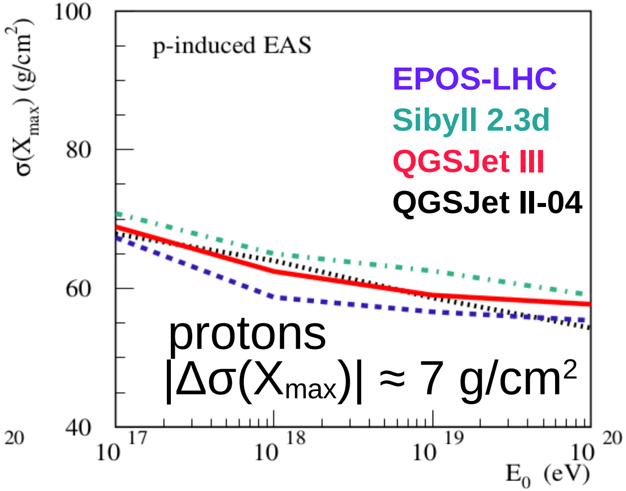
  ➔ alleviation of the “muon problem“ and **start of the “X_{max} problem“**

- modifications of macro-parameters (cross-section, multiplicity, elasticity) of hadronic interactions does not seem (preliminary) to be enough

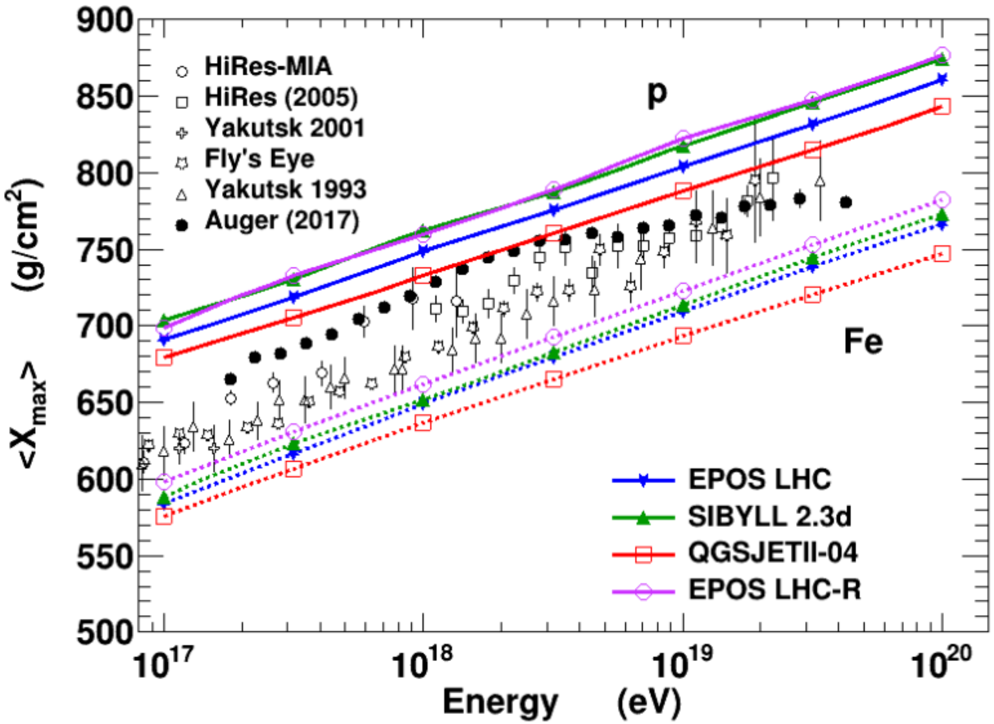
  ➔ different approach is needed: modifying micro parameters (production rates and energy spectra of secondary particles) or (not exclusively!) revisions of models of hadronic interactions

X_{max} fluctuations of Fe and elongation rate are very universal

[Phys. Rev. D 109 (2024) 094019]



[T. Pierog, EPOS-LHCR, Workshop on Tuning models of hadronic interactions]



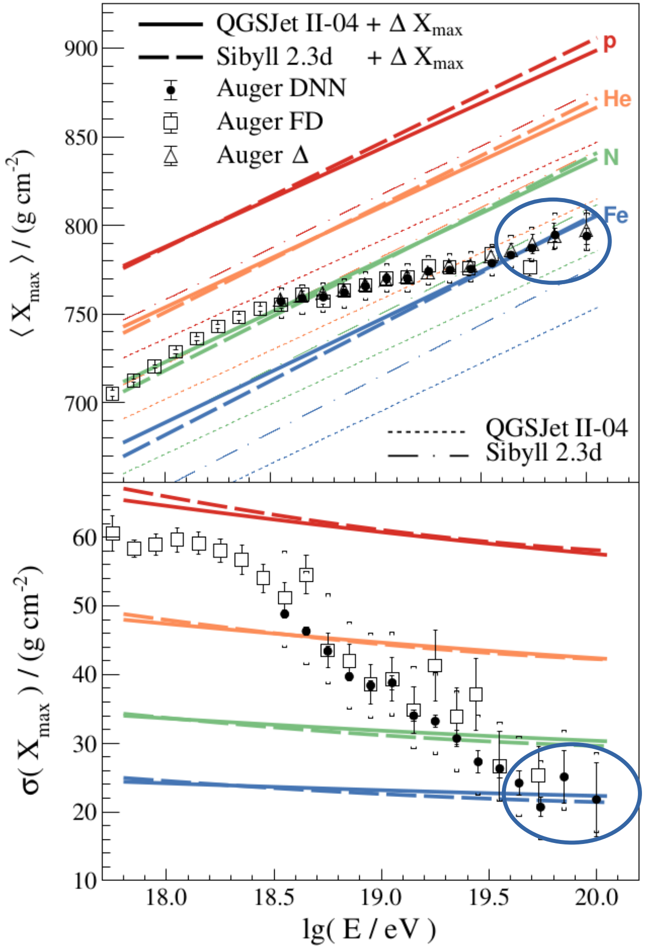
Correction of nuclear fragmentation in EPOS :
X_{max} RMS Fe
LHC=20g/cm2
LHC-R=24g/cm2
SIB=25g/cm2
QII=25g/cm2

} iron nuclei
$|\Delta\sigma(X_{max})| \approx 1$ g/cm^2

$|\Delta D_{10}| \approx 4$ g/cm^2 / lg E

Heavy-metal scenario

[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]



- Assumptions
  - X_{max} fluctuations and elongation rate from QGSJet II-04 and Sibyll 2.3d (bug in EPOS-LHC)
  - pure Fe nuclei above $10^{19.6}$ eV (~40 EeV)
  - freedom in the predicted X_{max} scale derived from Auger DNN [accepted in PRD, arXiv:2406.06319]

$$\Rightarrow \Delta X_{max} = 52 \pm 1 \,{}^{+11}_{-8}\ \mathrm{g/cm^2}$$
for QGSJET-II-04

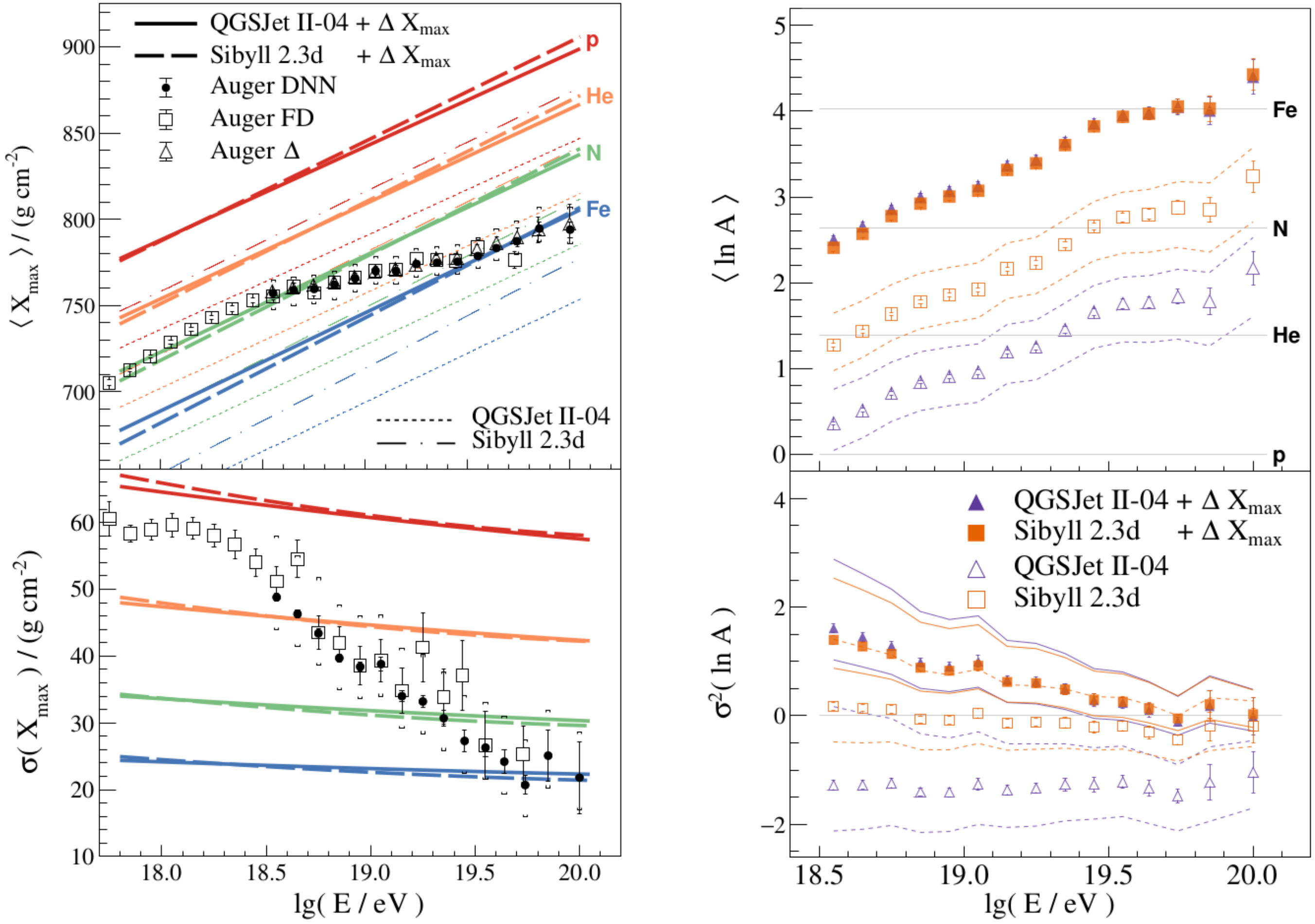
$$\Rightarrow \Delta X_{max} = 29 \pm 1 \,{}^{+12}_{-7}\ \mathrm{g/cm^2}$$
for SIBYLL 2.3d

[Phys. Rev. D 109 (2024) 102001]

	$R_{had}(\theta_{min})$	$R_{had}(\theta_{max})$	$\Delta X_{max}/(\mathrm{g/cm^2})$
EPOS-LHC	$1.15 \pm 0.01\,{}^{+0.20}_{-0.16}$	$1.16 \pm 0.01\,{}^{+0.14}_{-0.10}$	$22 \pm 3\,{}^{+11}_{-14}$
QGSJET-II-04	$1.24 \pm 0.01\,{}^{+0.22}_{-0.19}$	$1.18 \pm 0.01\,{}^{+0.15}_{-0.12}$	$47^{+2}_{-1}\,{}^{+9}_{-11}$
SIBYLL 2.3d	$1.18 \pm 0.01\,{}^{+0.21}_{-0.17}$	$1.15 \pm 0.01\,{}^{+0.15}_{-0.11}$	$29 \pm 2\,{}^{+10}_{-13}$

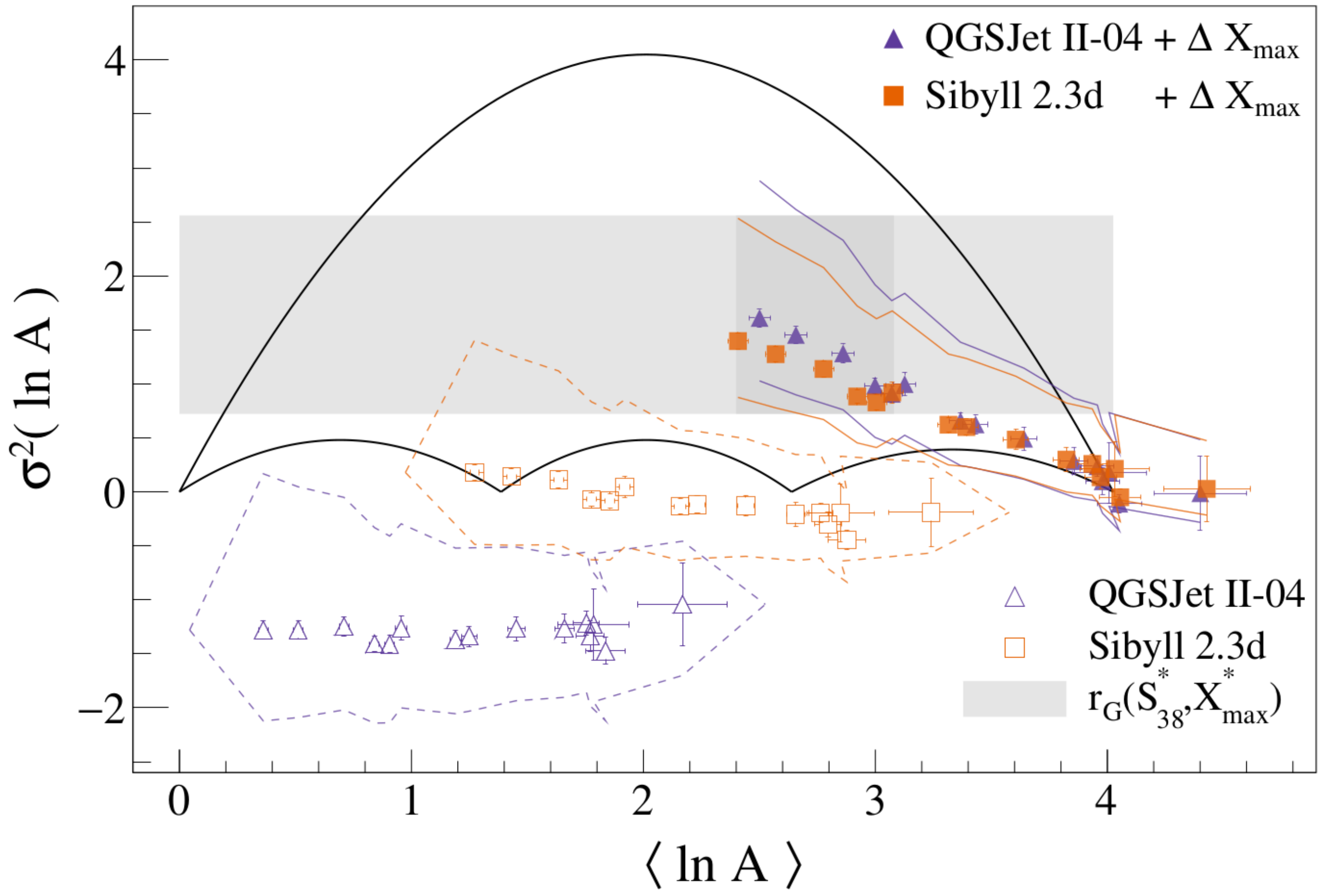
Heavy-metal scenario: ln A moments

[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]



Heavy-metal scenario: ln A moments

[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]



- ΔX_{max} consistent with results from $[X_{max},S(1000)](\theta)$ fits
  [Phys. Rev. D 109 (2024) 102001]
- $\sigma^2(\ln A)$ consistent with result from X_{max}-S_{38} correlation
  [Phys. Lett. B 762 (2016) 288]
- umbrella plot, $\sigma^2(\ln A)$ vs. <ln A>, generally more physical

Heavy-metal scenario: energy evolution of individual primary fractions and fluxes

[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]

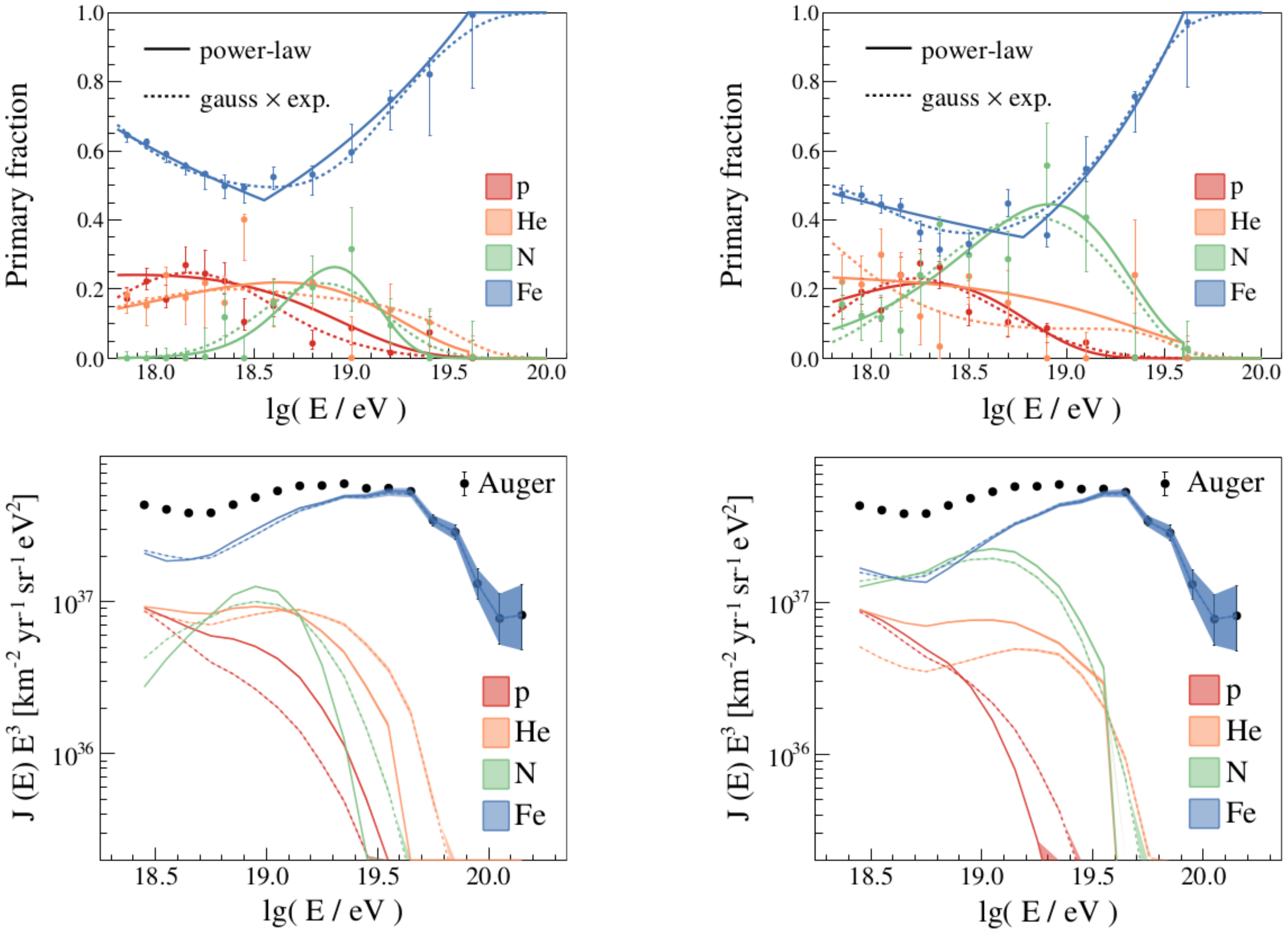
1) parameterization of energy evolution of primary fractions using Auger X_{max} data

[Phys. Rev. D 90 (2014) 122005]

2) derivation of fluxes of primary species from Auger energy spectrum

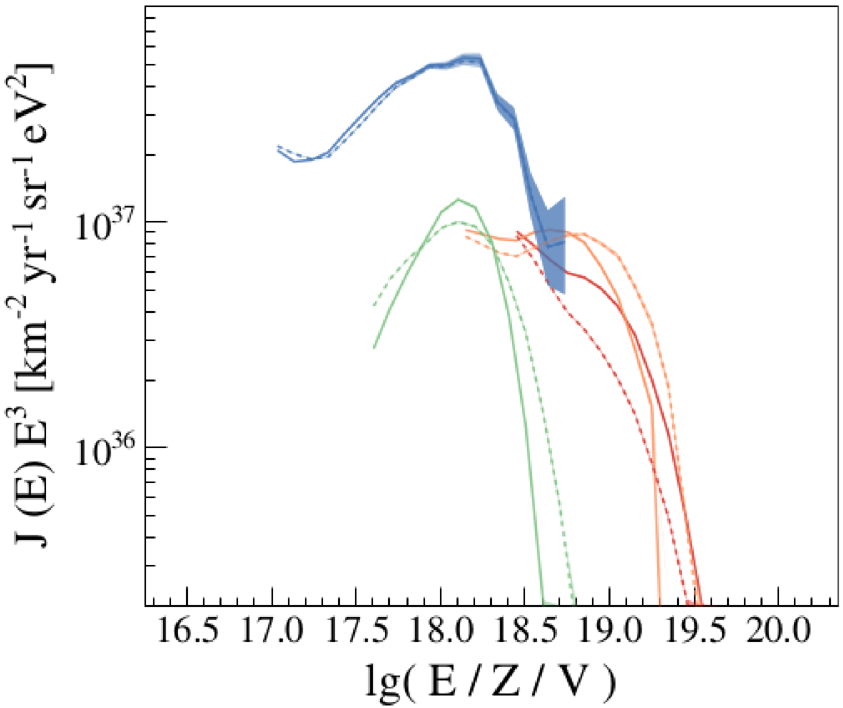
[PRD 102 (2020) 062005]

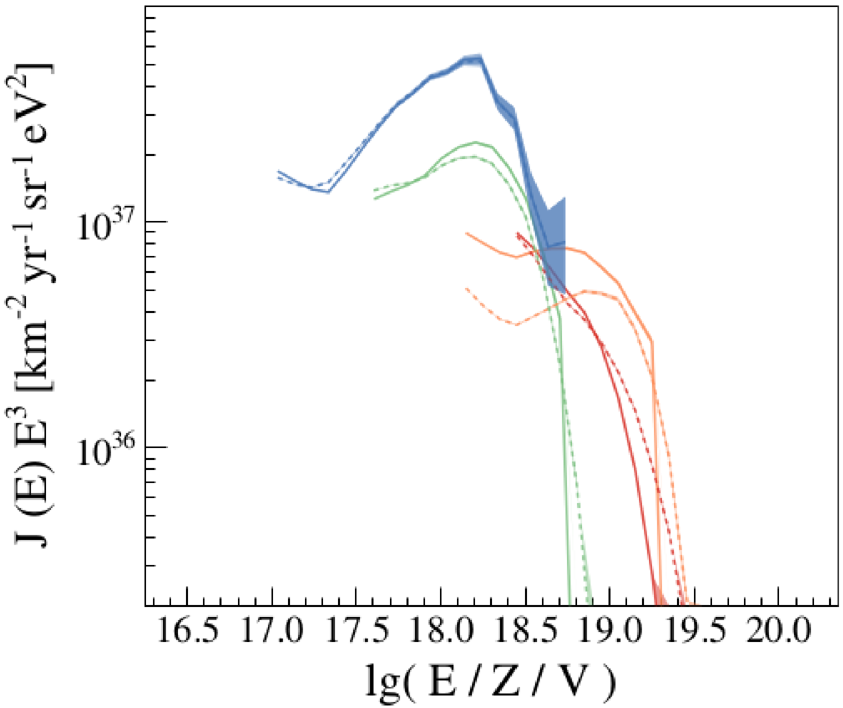
instep feature (~15 EeV) caused by fading of N



Heavy-metal scenario: energy evolution of rigidity (E/Z)

[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]

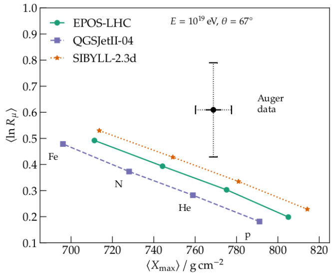


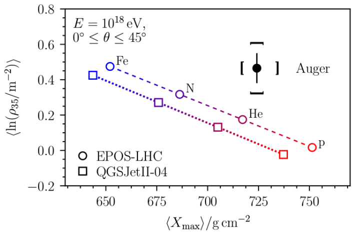


Fe and N nuclei might have a common origin

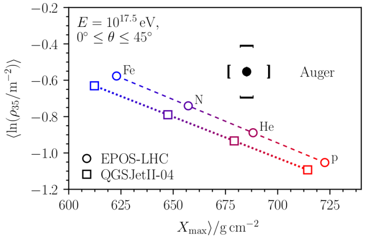
Heavy-metal scenario: number of muons

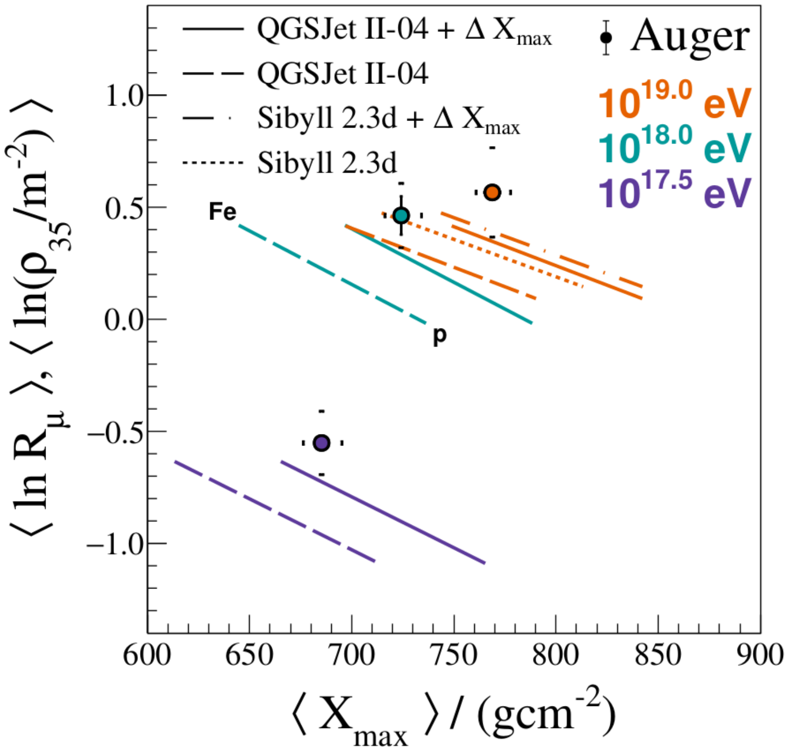
[Phys. Rev. Lett. 126 (2021) 152002]



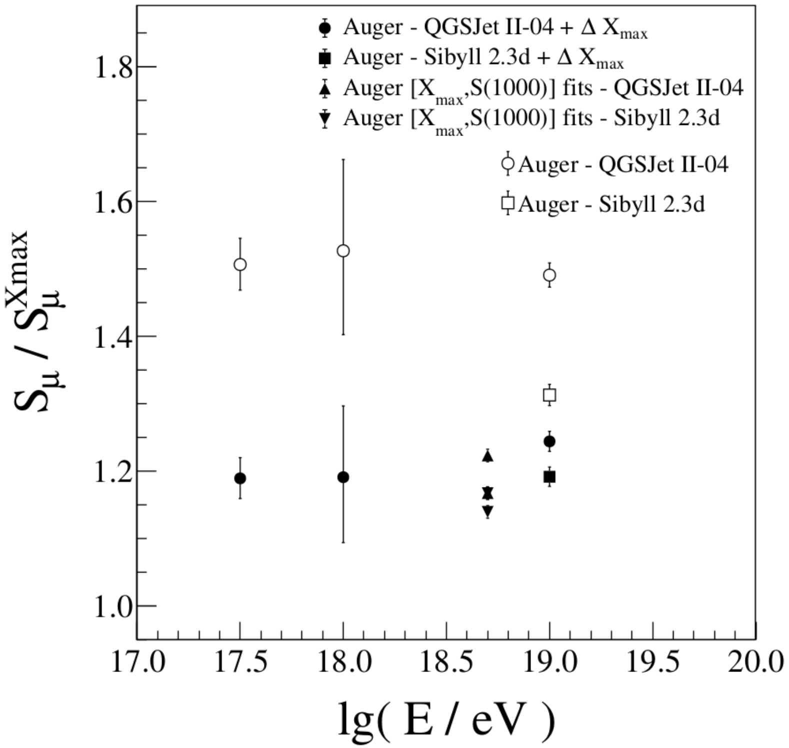


[Eur. Phys. J. C 80 (2020) 751]





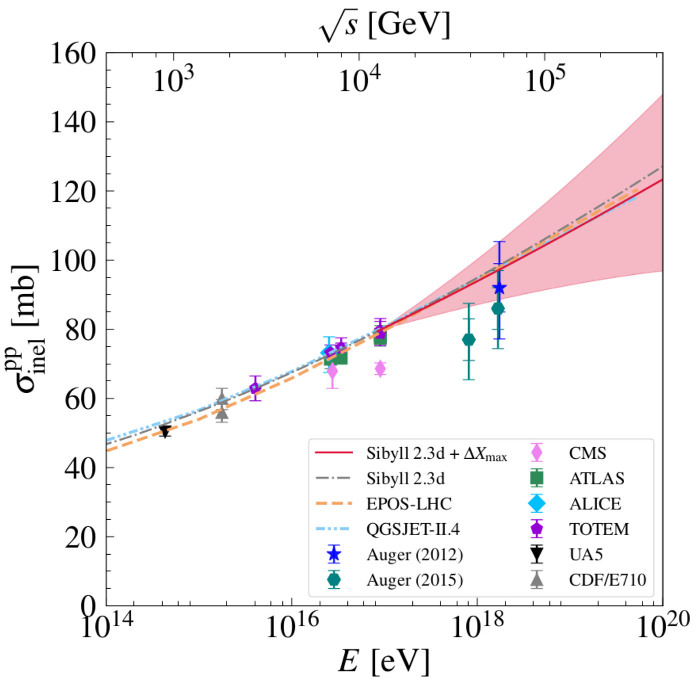
[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]

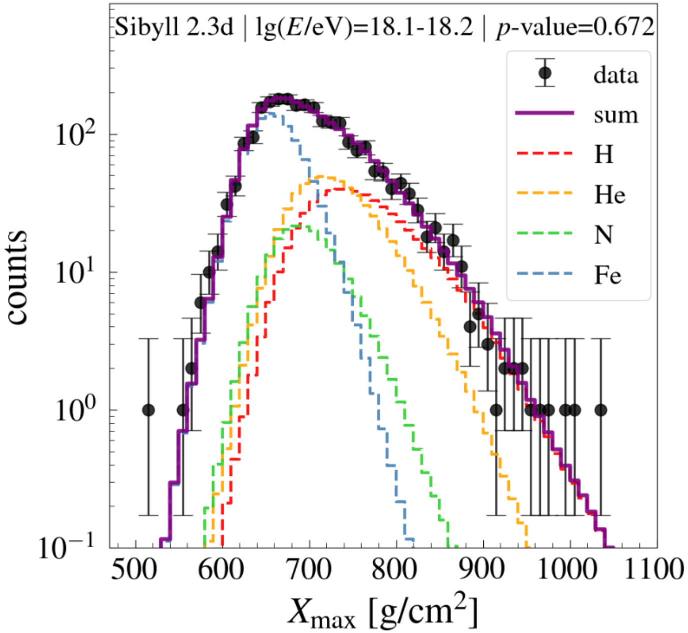


Muon problem alleviated to ~20%, ~independently on energy

Heavy-metal scenario: cross-section modification

[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]

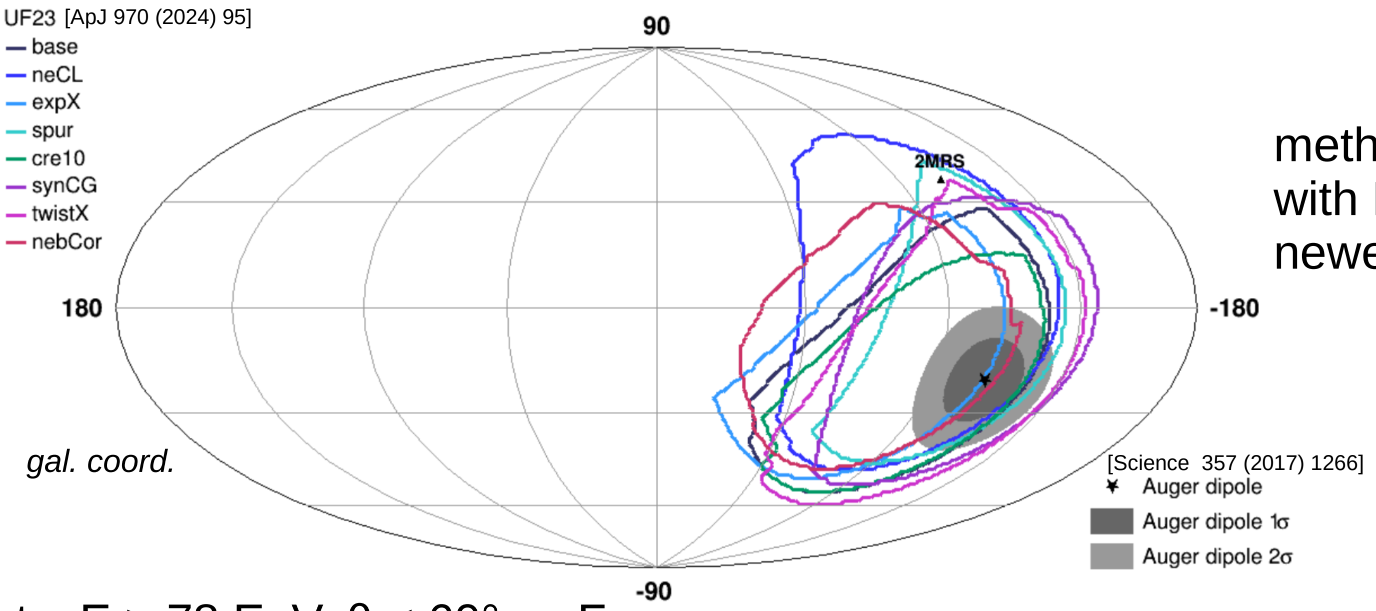




- X_{max} data from [Phys. Rev. D 90 (2014) 122005] , method from [O. Tkachenko for Pierre Auger Coll. PoS(ICRC2023)438]
- no modification of cross-section in models is needed
- very good description of X_{max} distributions obtained

Heavy-metal scenario: backtracking in Galactic magnetic field

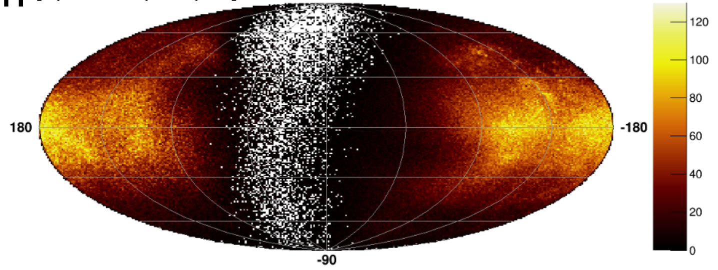
[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier, UHECR 2024]



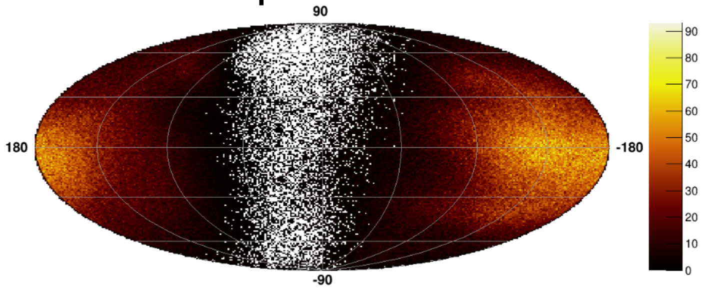
method from [A. Bakalová, JV, P. Trávníček, JCAP12 (2023) 016] with H-m composition and newer model of GMF

➔ constraints on direction of an extragalactic dipole above 8 EeV

89 events, E > 78 EeV, θ < 60° as Fe, from [ApJS 264 (2023) 50]



Isotropic distribution

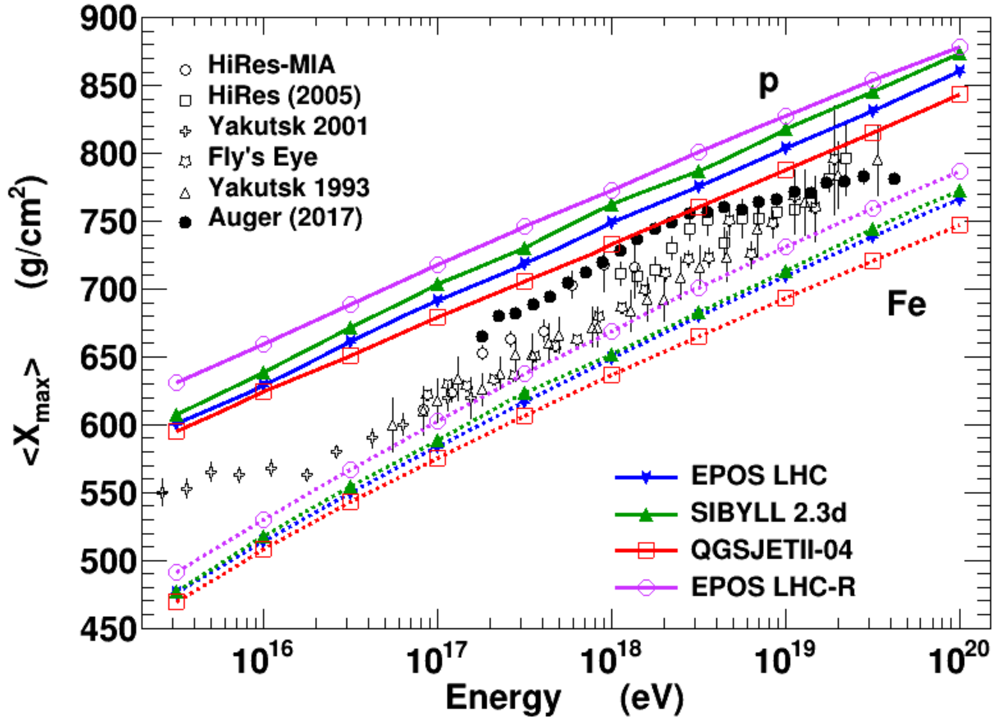


low rigidity causing de-magnification of sources towards GC

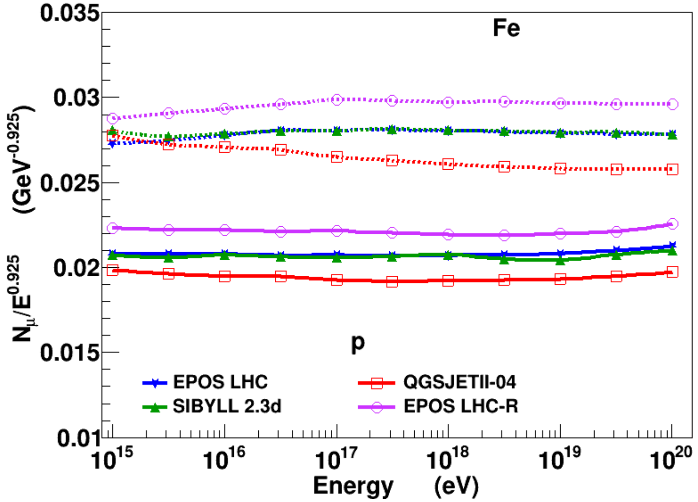
EPOS-LHCR is approaching !

[T. Pierog, Dec 2024 - CRs and ν in MM era, APC, Paris, France]

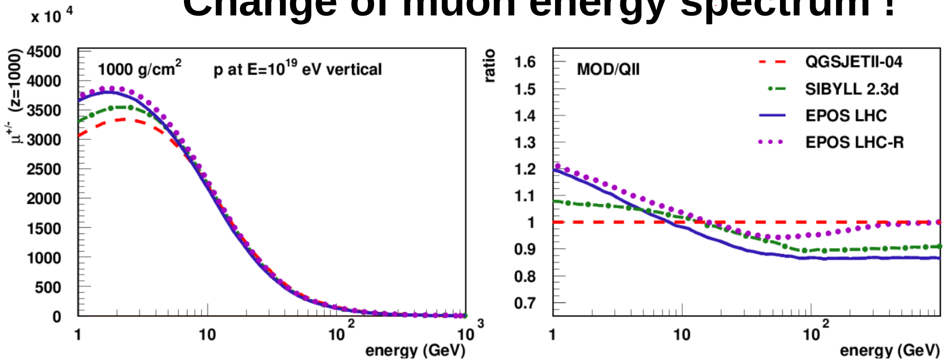
Deeper X_{max} by ~20-30 g/cm²!



More muons by ~10% !



Change of muon energy spectrum !

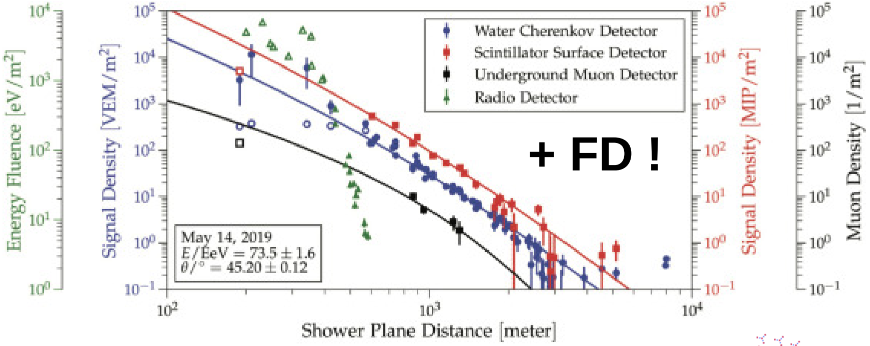


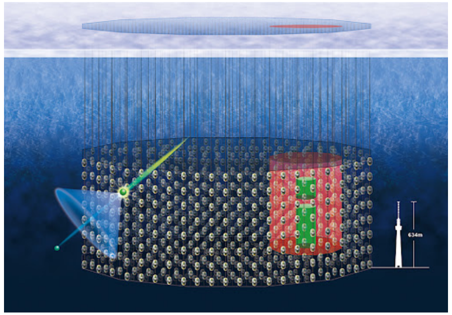
More air-shower studies yet to come! Stay tuned

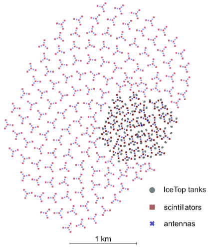
- **new models** of hadronic interactions (EPOS 4(LHCR), QGSJet III, Sibyll **?, ...) and **new air-shower generator** (CORSIKA 8) are expected to decrease the systematic uncertainties on mass composition of cosmic rays

    ➔ **p + O collisions at the end of Run 3** at LHC are very important !

- **AugerPrime** (2024-2035) will be the best testing facility for forward hadronic interactions at **√s ~ 10-200 TeV**
- + **IceCube-Gen2** (2032-?) at **√s ~ 1-50 TeV**
- + **LHAASO** (2023-?) at **√s ~ 0.1-1 TeV** ?
- and new methods (Machine Learning) and more data ...



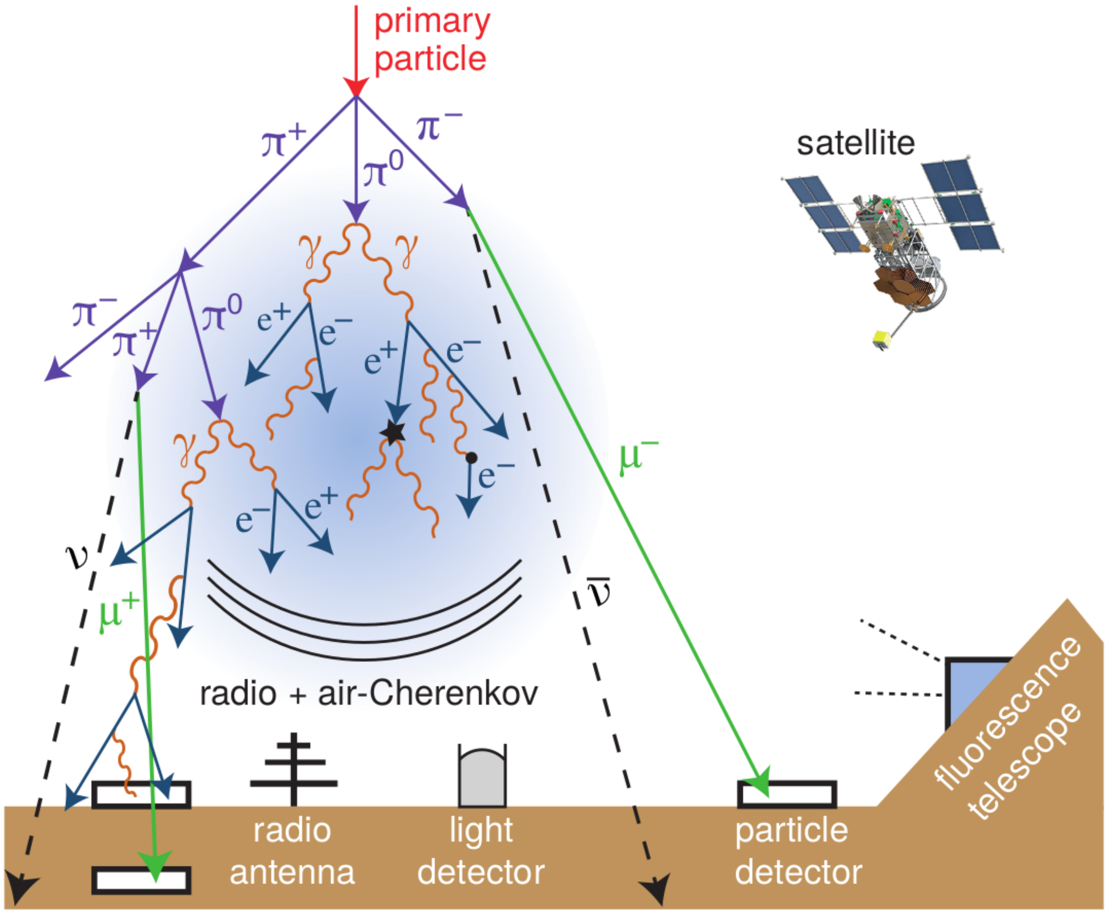




Thank you for your attention !

Backup slides

Air-shower Measurements

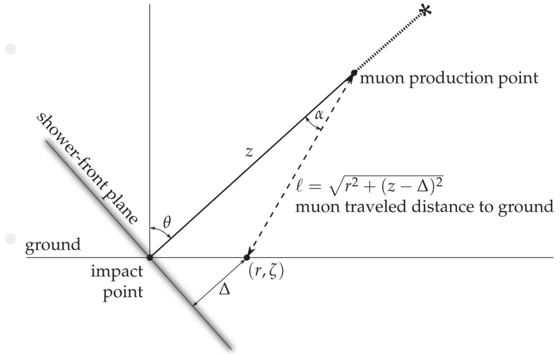


Observables relevant to hadronic interaction models

SD signal

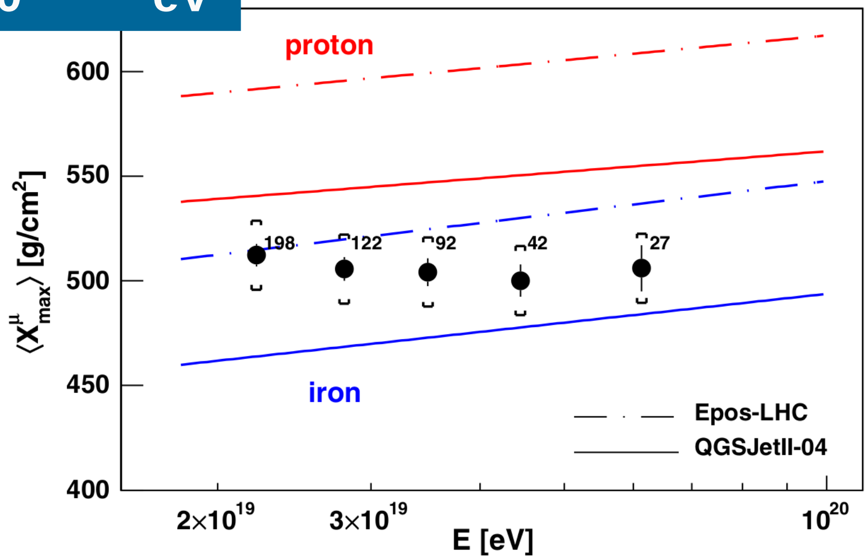
- muon content
  - from buried scintillators, θ<60°
  - from N_{19}, θ>65°

- muon production depth
  - for core distance r > 1500m, θ>65°

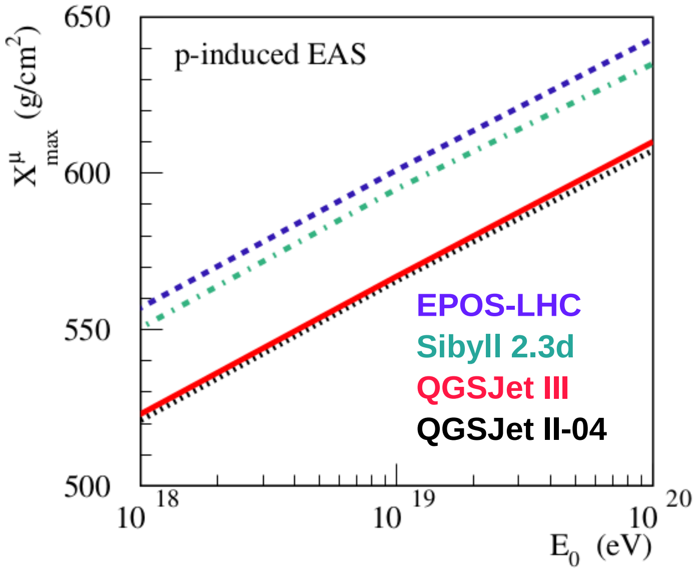


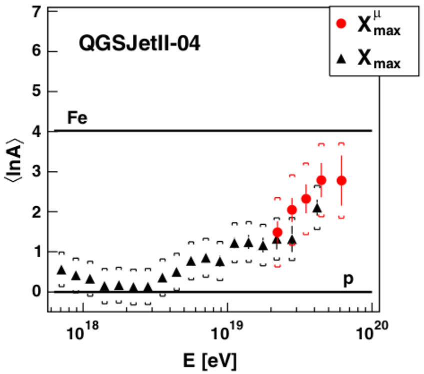
$10^{19.3\text{-}19.8}$ eV

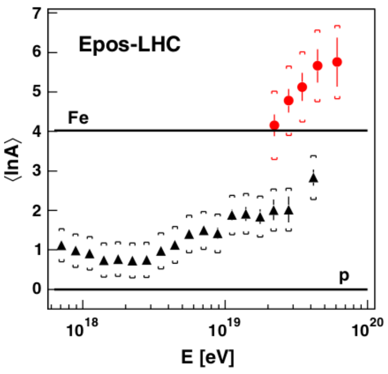
[Phys. Rev. D 90 (2014) 012012]



[Phys. Rev. D 109 (2024) 094019]







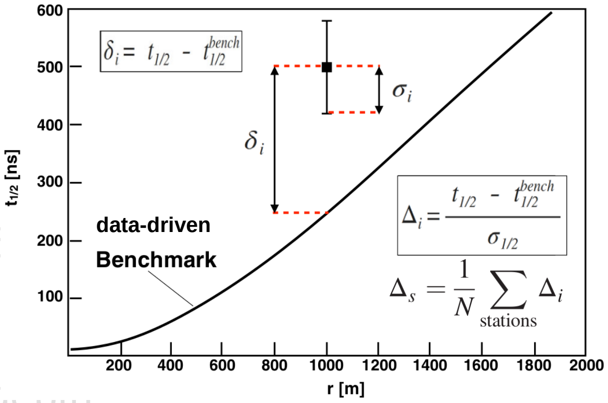
- EPOS-LHC and (likely also) Sibyll 2.3d too deep ~2σ
- MPD tunable by pion diffraction (loosely constrained by current accelerators data)

Observables relevant to hadronic interaction models

SD signal

- muon content
  - from buried scintillators, θ<6
  - from N_{19}, θ>65°
- muon production depth
  - for core distance r > 1500m, θ>65°
- muon energy spectru
  - from attenuation w θ and r
- rise time of signal vs. r

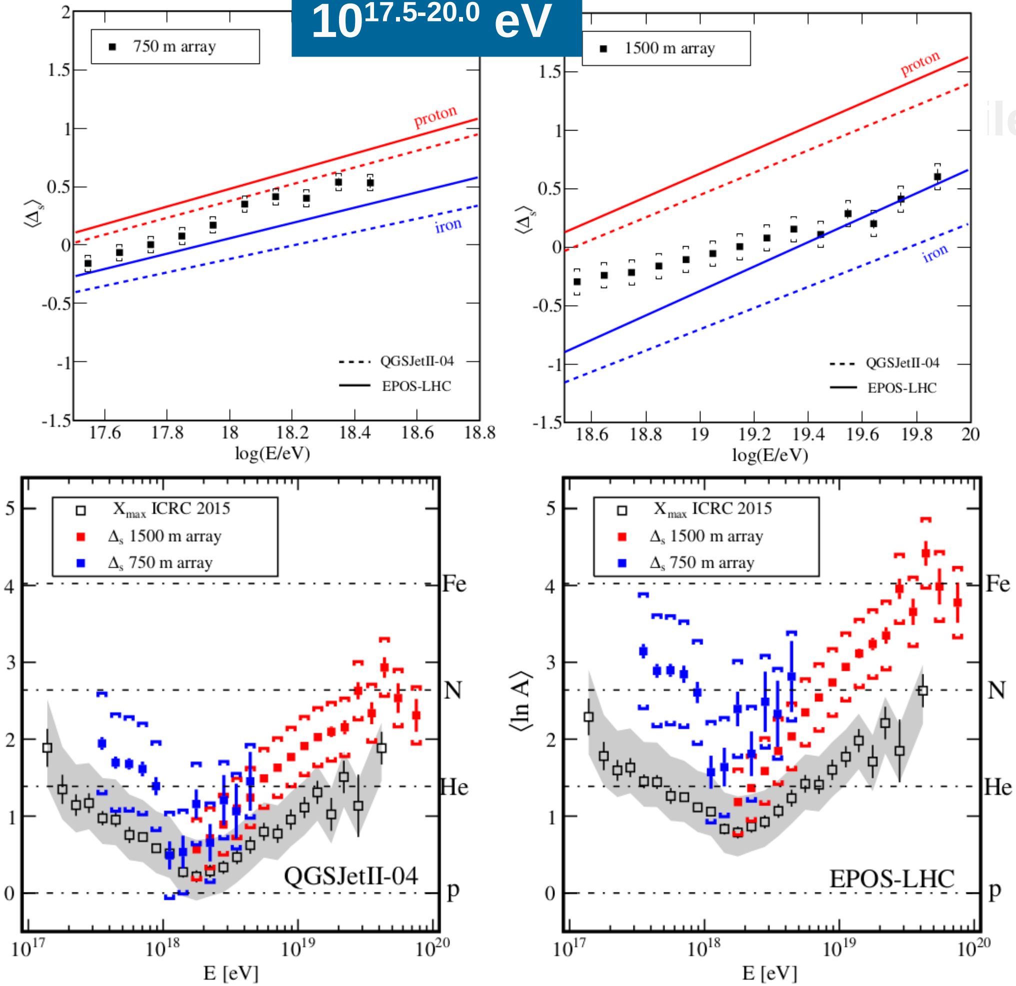
[Phys. Rev. D 96 (2017) 122003]



$$\langle \ln A \rangle = \ln 56 \, \frac{\langle \Delta_s \rangle_p - \langle \Delta_s \rangle_{data}}{\langle \Delta_s \rangle_p - \langle \Delta_s \rangle_{Fe}}$$

~1-2σ inconsistent interpretation of <ln A> between Δ_s and X_{max}

$10^{17.5\text{-}20.0}$ eV



Observables relevant to hadronic interaction models

$10^{17.8\text{-}19.5}$ eV

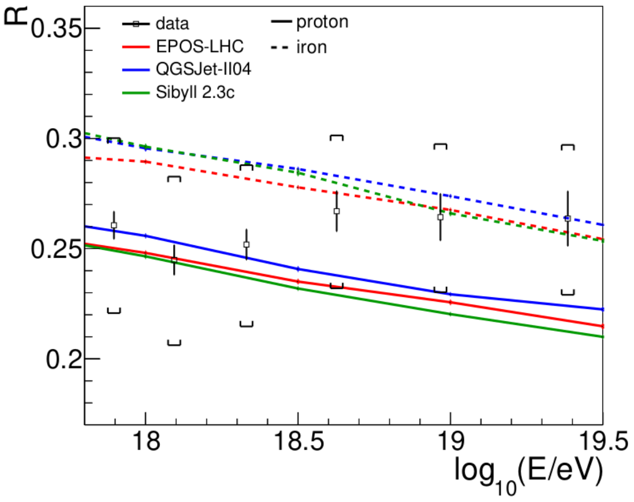
[JCAP 03 (2019) 018]

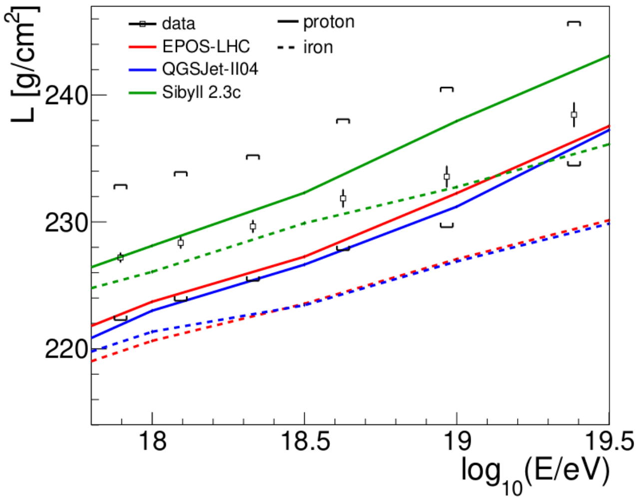
SD signal

- muon content
  - from buried scintillators, θ<60°
  - from N_{19}, θ>65°

$$f_{\mathrm{GH}}(X) = (\mathrm{d}E/\mathrm{d}X)_{\max}\left(\frac{X-X_0}{X_{\max}-X_0}\right)^{\frac{X_{\max}-X_0}{\lambda}}\exp\left(\frac{X_{\max}-X}{\lambda}\right)$$

$$(\mathrm{d}E/\mathrm{d}X)' = \left(1+R\,\frac{X'}{L}\right)^{R^{-2}}\exp\left(-\frac{X'}{R\,L}\right)$$





FD longitudinal profile

- so far consistent within ~2σ with models
- smaller systematics on aerosol measurement could improve constraints

- p-air cross-section from tail of X_{max} distribution

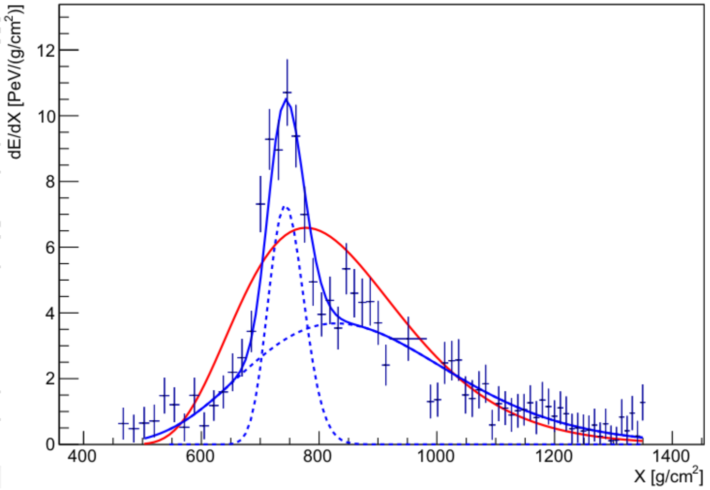
- average shape of longitudinal profiles

- frequency of anomalous showers

Observables relevant to hadronic interaction models

[EPJ Web Conf. 144 (2017) 01009]

FD profile

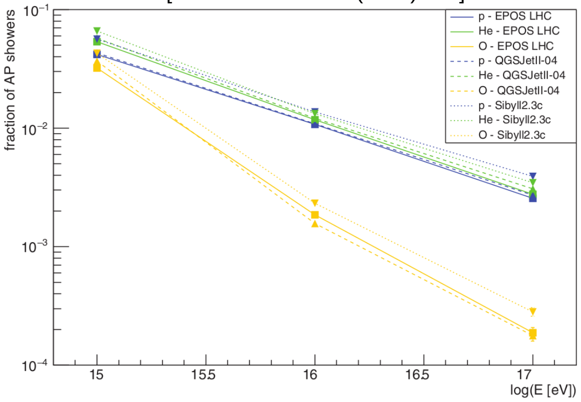


$10^{17.2\text{-}18.5}$ eV ?

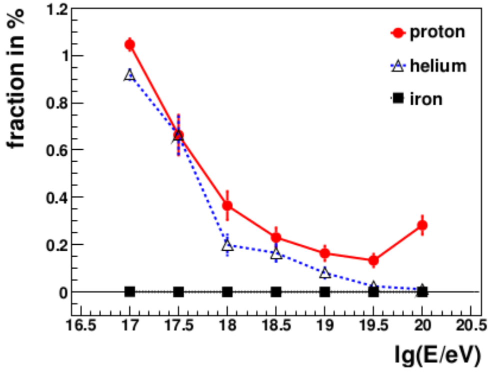
FD longitudinal profile

- ‰ effect at 10^{18}eV, % effect at 10^{16}eV
- hard to reject presence of clouds
  ➔ additional cloud measurement is needed
- possible constraints on presence of lightest primaries (and cross-section/elasticity)
- no application to the data yet

[Astron. Nachr. 340 (2019) 234]



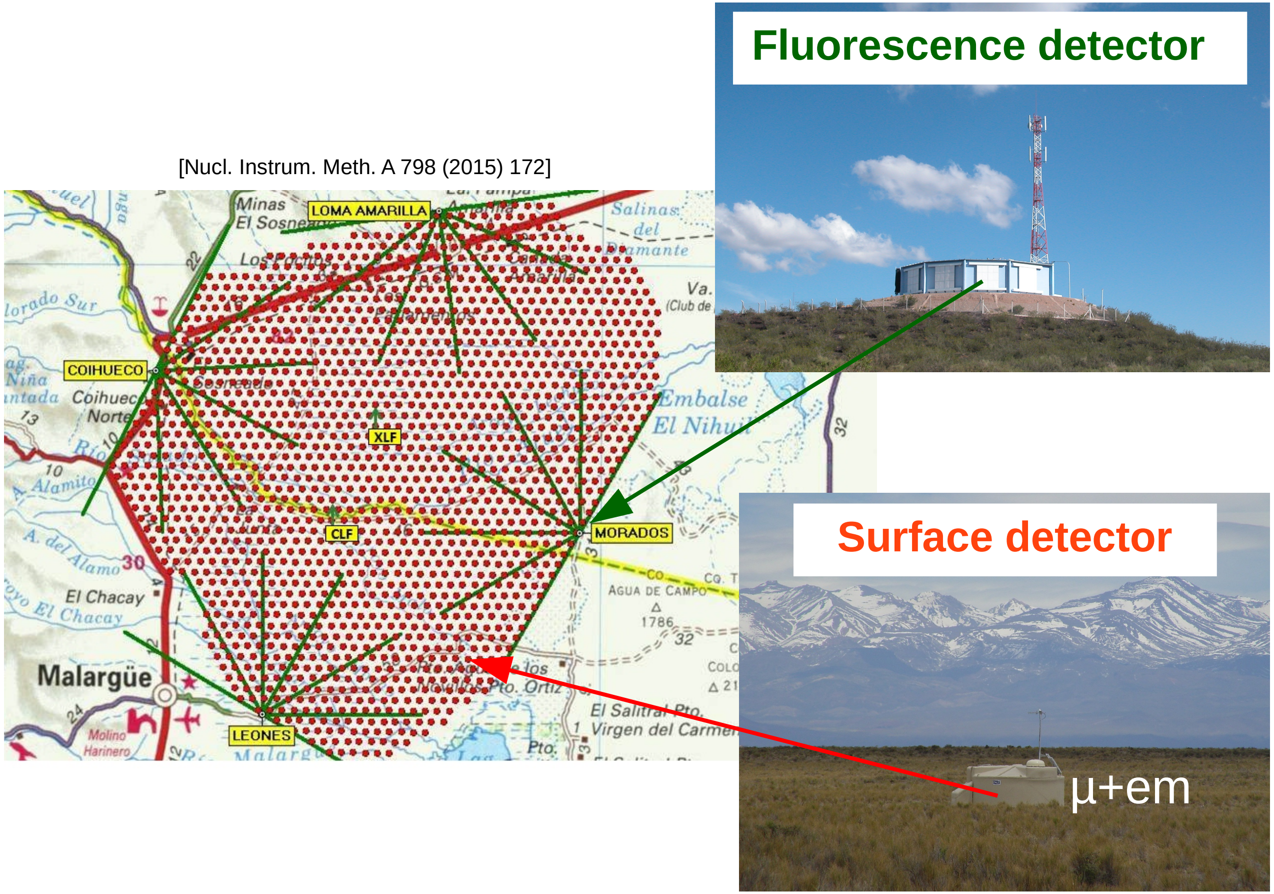
[arXiv:1111.0504]

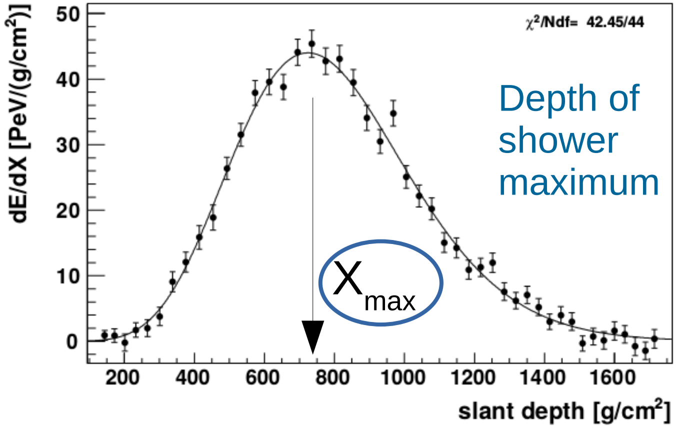


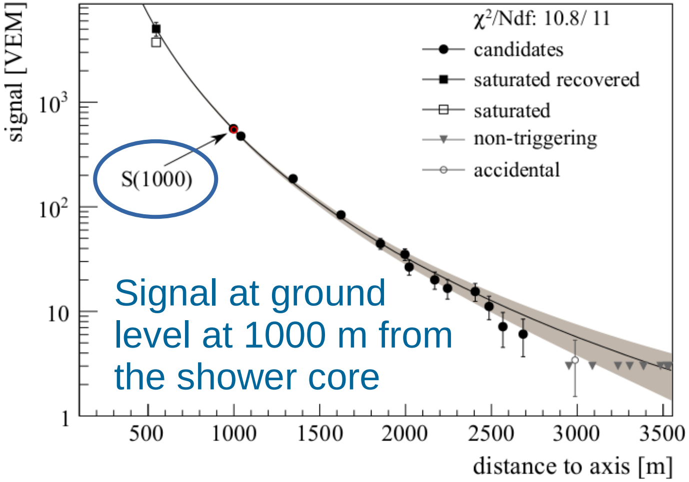
- frequency of anomalous showers

Hybrid detection at the Pierre Auger Observatory

[Nucl. Instrum. Meth. A 798 (2015) 172]





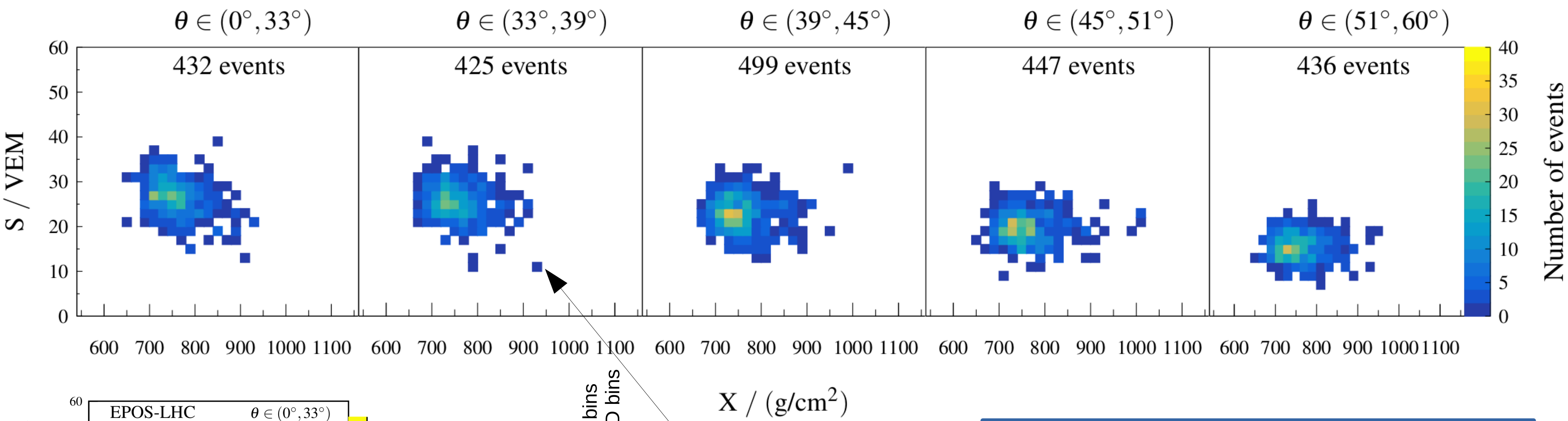


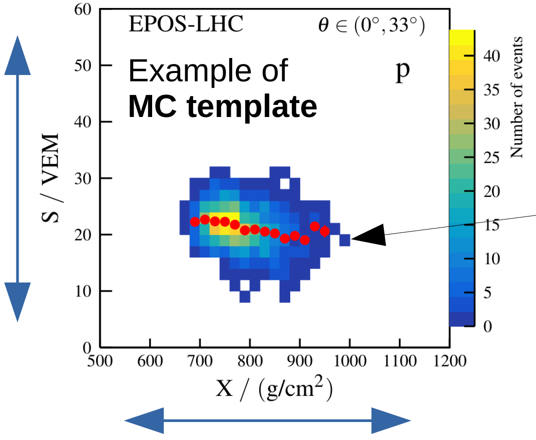
Auger data:
2239 HQ events for $10^{18.5\text{-}19.0}$ eV

Method

$$S = S(1000)\left(\frac{E^{\mathrm{ref}}}{E_{\mathrm{FD}}}\right)^{1/B} \qquad X = X_{\max} + D\,\lg\left(\frac{E^{\mathrm{ref}}}{E_{\mathrm{FD}}}\right)$$

$E^{ref} = 10^{18.7}$ eV





θ bins
2D bins

$$\ln \mathscr{L} = \begin{cases} \sum_k \sum_j (C_{jk} - n_{jk} + n_{jk} \ln \frac{n_{jk}}{C_{jk}}), & n_{jk} > 0 \\ \sum_k \sum_j C_{jk}, & n_{jk} = 0 \end{cases}$$

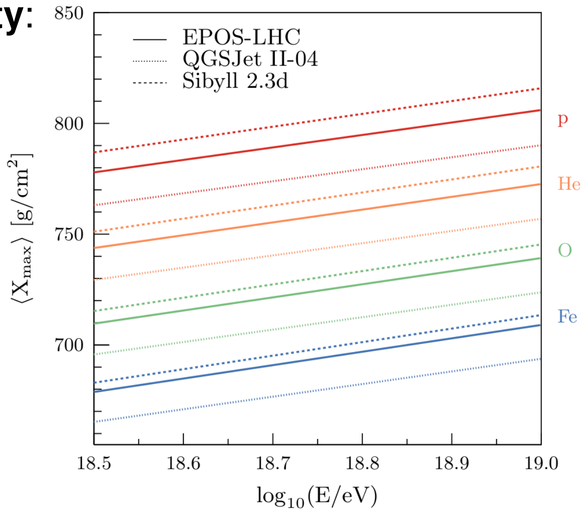
- **Freedom** in X_{max} (ΔX_{max}) and S(1000) ($R_{had}(\theta)$) and primary fractions
- Change of S_{had} and S_{em} due to ΔX_{max} incorporated

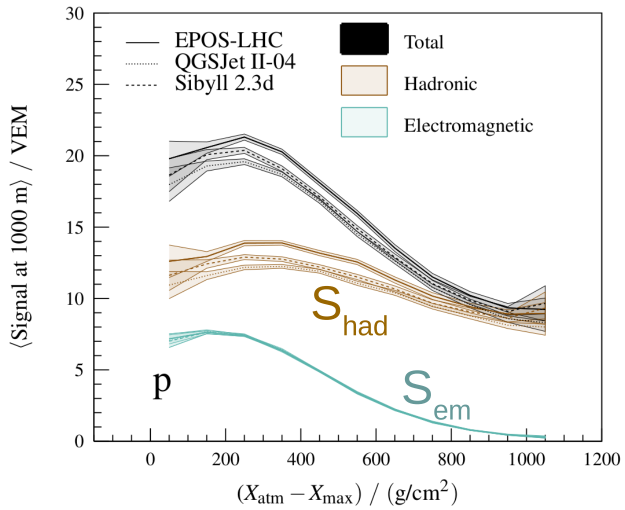
Simultaneous log-likelihood ratio fit of **two-dimensional distributions** of X_{max} and S(1000) in 5 zenith-angle bins with **MC templates** for combinations of four primary nuclei (p,He,O,Fe)

Motivations for modifications of MC predictions

- Properties of **4-component shower universality**:

  [Astropart. Phys. 87 (2017) 23, Astropart. Phys. 88 (2017) 46]
  - $S(1000) = S_{had} + S_{em}$
  - S_{em} very universal
- **Main differences** between model predictions:
  - Scale of $\langle X_{max} \rangle$ and $\langle S_{had} \rangle(\theta)$ are **approx. primary and energy independent**





$$X_{atm} = 880/\cos\theta \;\; g/cm^2$$

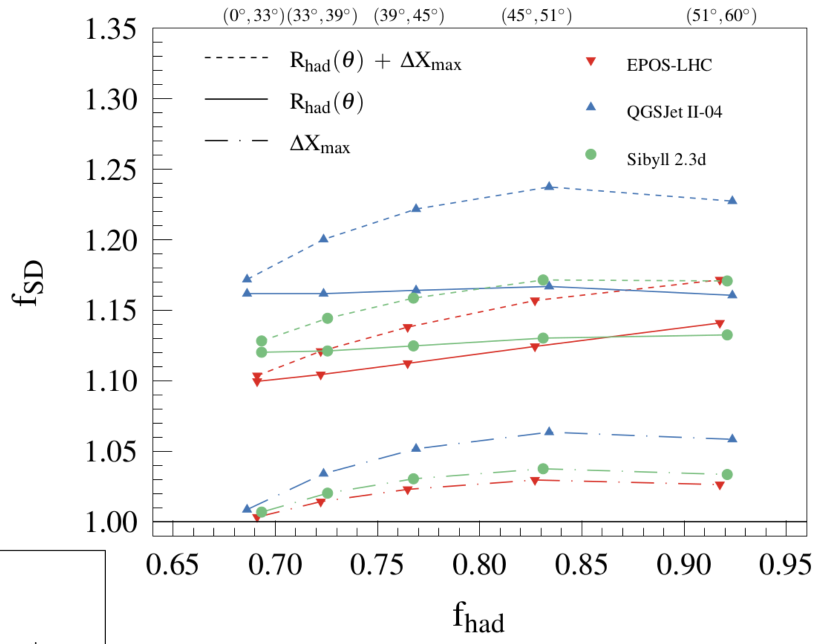
Caveat: no modifications in fluctuations or mass-depencies etc. considered

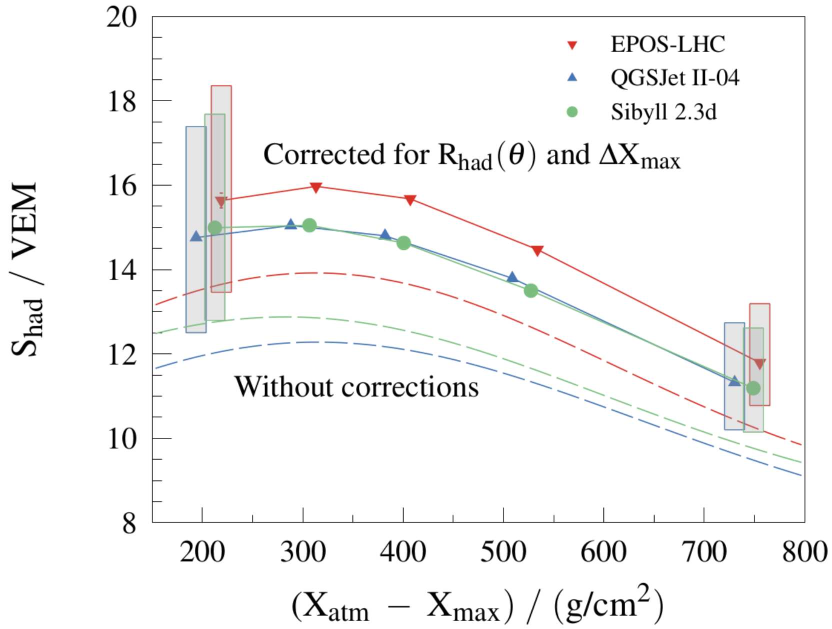
ad-hoc modifications

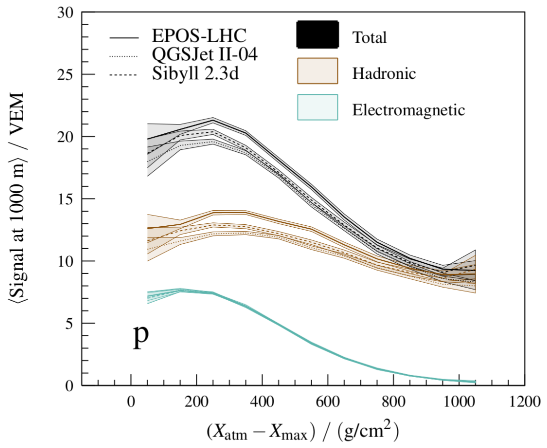
$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

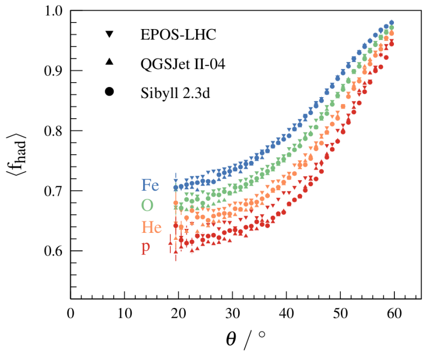
$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

Effect of modified X_{max} on the ground signal









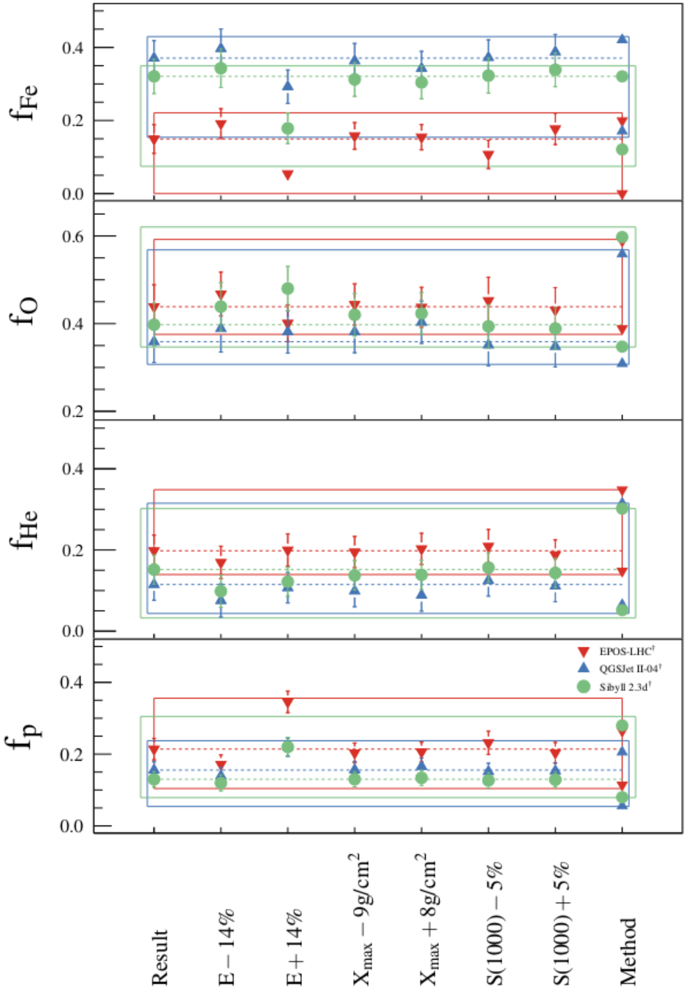
Assumption on primary species

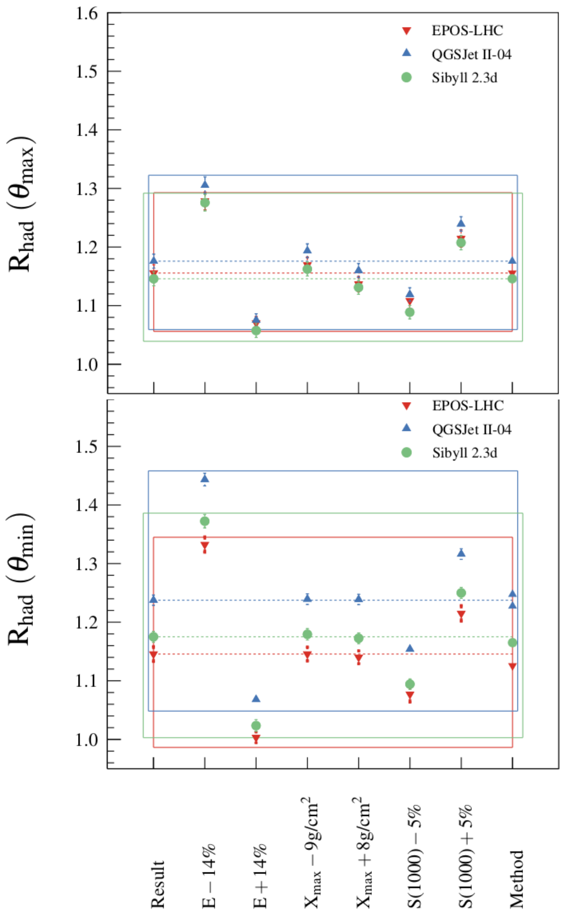
- ΔX_{max} decreases by about 5-7, 10-17 and 30-40 g/cm^2 and $R_{had}(\theta)$ increases by about 2-5%, 4-9% and 15-20% when the heaviest primary Fe is replaced by Si, O and He, respectively

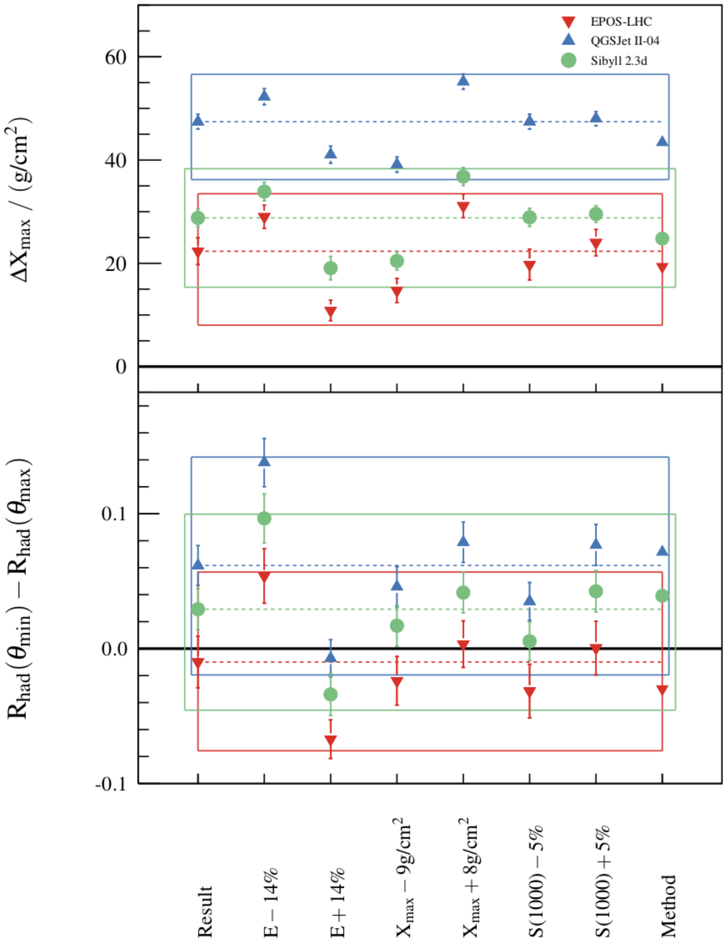
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
p He	518.3	633.5	563.5
p He O	467.5	523.3	486.6
p He O Fe	451.9	476.3	451.6

Significance of improvement of data description above 5σ

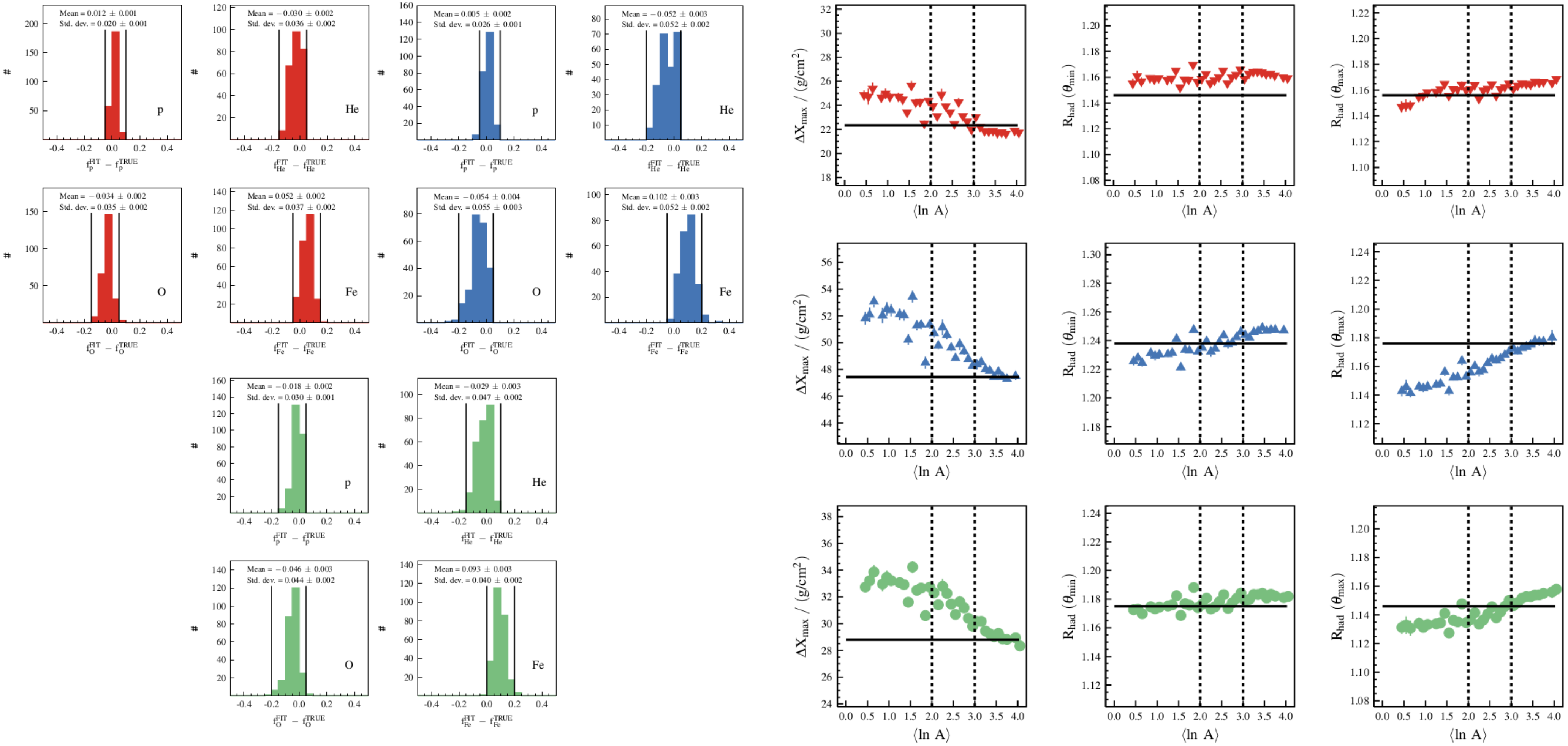
Systematic uncertainties







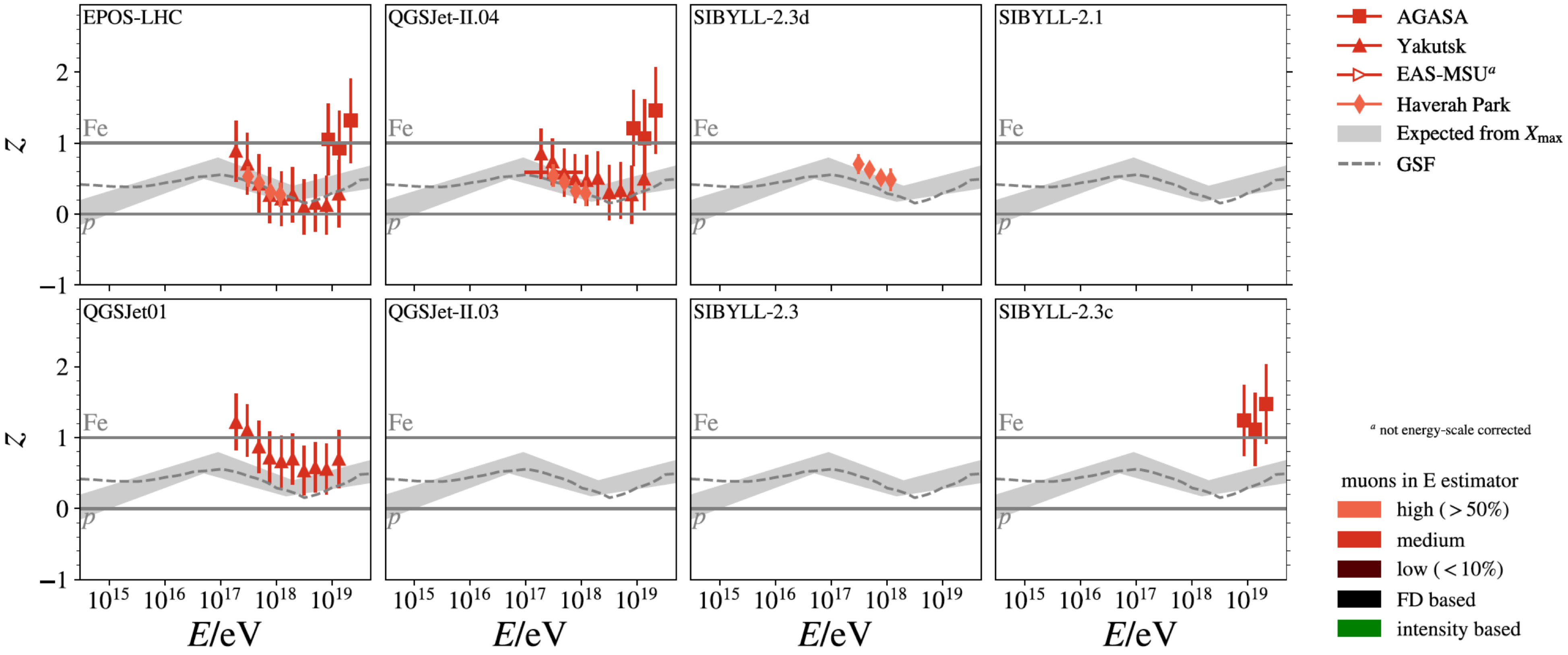
MC-MC tests


Mean = 0.012 ± 0.001
Std. dev. = 0.020 ± 0.001
p
Mean = −0.030 ± 0.002
Std. dev. = 0.036 ± 0.002
He
Mean = 0.005 ± 0.002
Std. dev. = 0.026 ± 0.001
p
Mean = −0.052 ± 0.003
Std. dev. = 0.052 ± 0.002
He
Mean = −0.034 ± 0.002
Std. dev. = 0.035 ± 0.002
O
Mean = 0.052 ± 0.002
Std. dev. = 0.037 ± 0.002
Fe
Mean = −0.054 ± 0.004
Std. dev. = 0.055 ± 0.003
O
Mean = 0.102 ± 0.003
Std. dev. = 0.052 ± 0.002
Fe
Mean = −0.018 ± 0.002
Std. dev. = 0.030 ± 0.001
p
Mean = −0.029 ± 0.003
Std. dev. = 0.047 ± 0.002
He
Mean = −0.046 ± 0.003
Std. dev. = 0.044 ± 0.002
O
Mean = 0.093 ± 0.003
Std. dev. = 0.040 ± 0.002
Fe
#
$f_p^{FIT} - f_p^{TRUE}$
$f_{He}^{FIT} - f_{He}^{TRUE}$
$f_O^{FIT} - f_O^{TRUE}$
$f_{Fe}^{FIT} - f_{Fe}^{TRUE}$
ΔX_{max} / (g/cm^2)
R_{had} (θ_{min})
R_{had} (θ_{max})
⟨ln A⟩

Experiments using muons for energy estimation

[PoS(ICRC2023)466, L.Cazon Jan 2024 - Workshop on the Tuning of hadronic interactions]

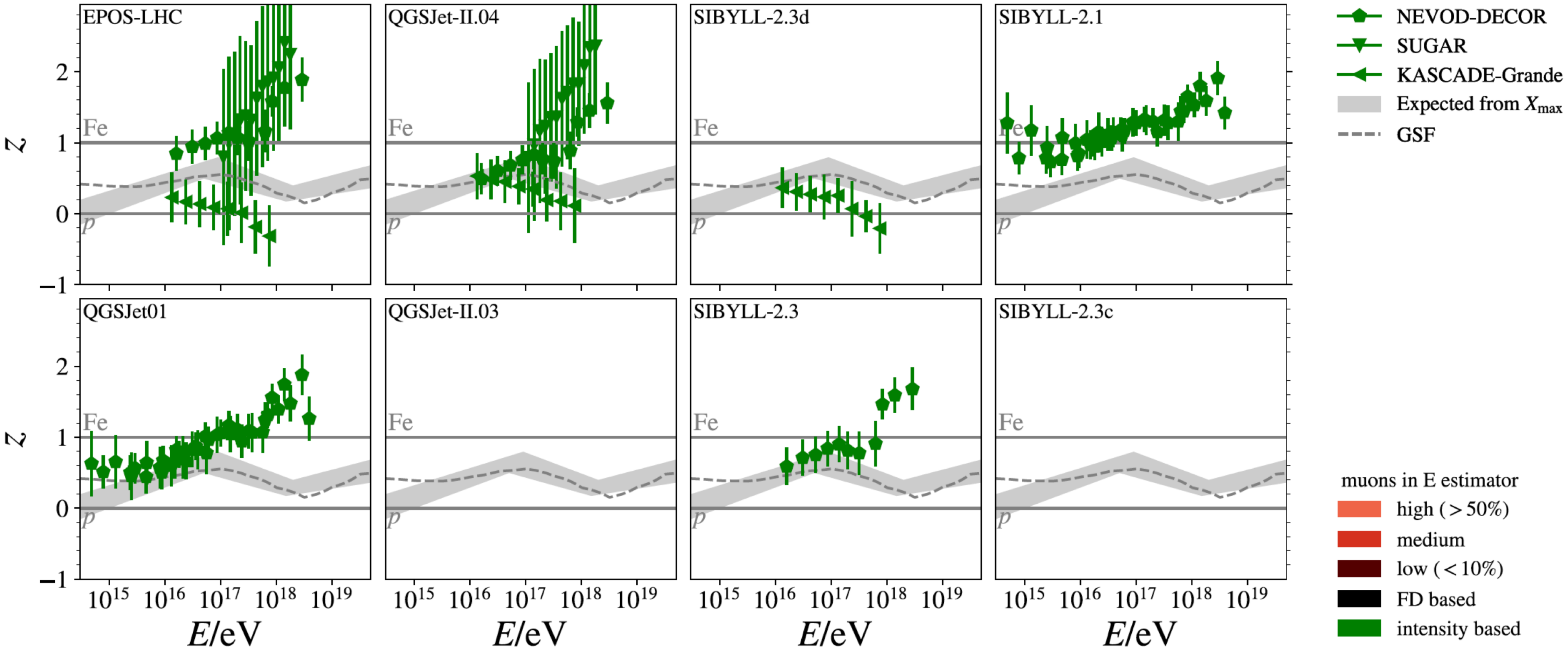
- Classification according to the muon contamination in the estimated primary energy.



Experiments applying CR intensity estimation of energy

[PoS(ICRC2023)466, L.Cazon Jan 2024 - Workshop on the Tuning of hadronic interactions]

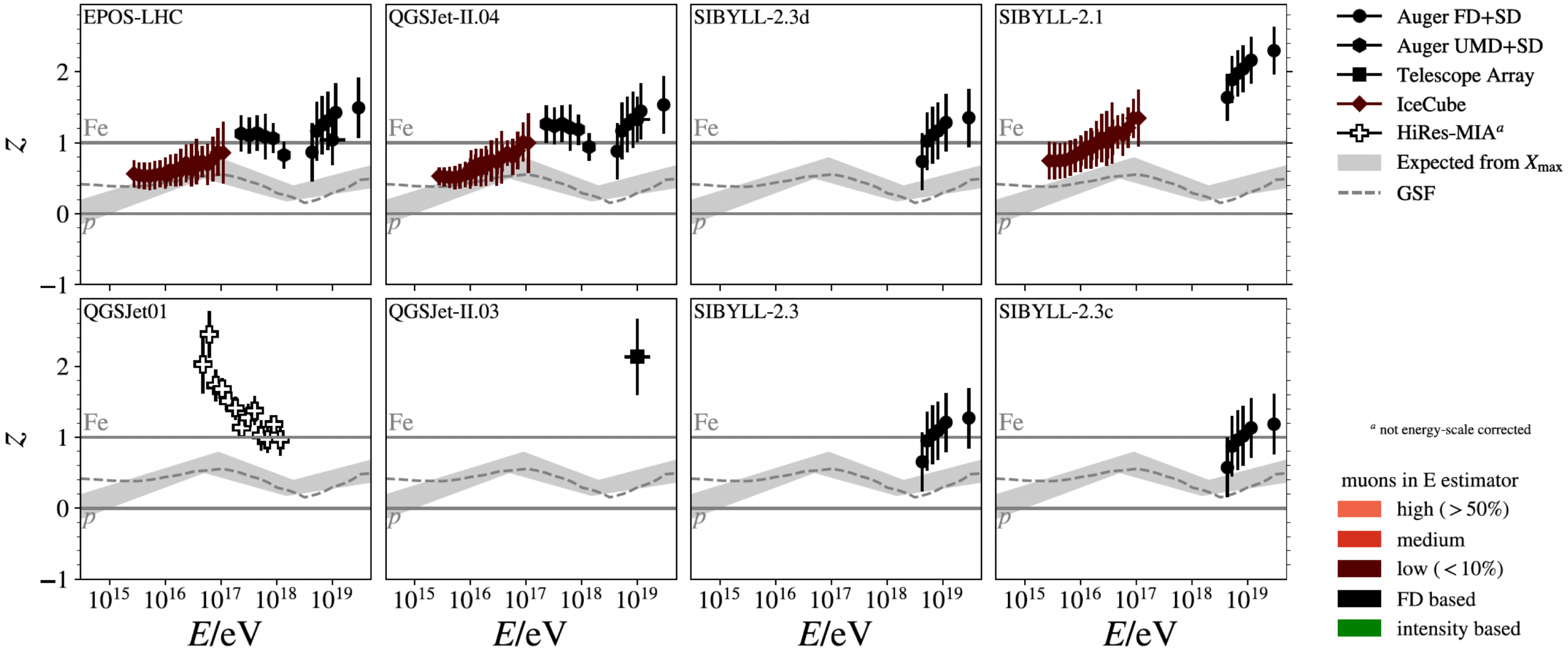
- Classification according to the muon contamination in the estimated primary energy.



Experiments using ~muon independent energy estimator

[PoS(ICRC2023)466, L.Cazon Jan 2024 - Workshop on the Tuning of hadronic interactions]

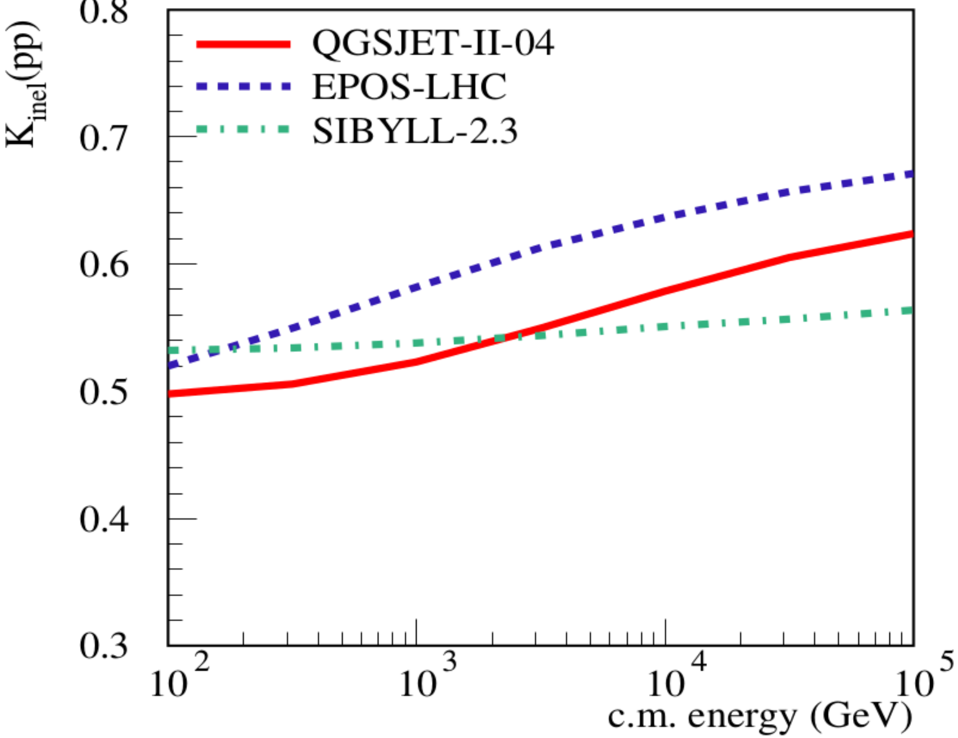
- Classification according to the muon contamination in the estimated primary energy.



Possible mass-(in)dependence of X_{max} shift

“changing the normalization of energy dependence“ ➔ mass independent modifications

[arXiv:1612.09461 [astro-ph.HE]]



multiplicity: $N \propto N_0 \cdot E^{\alpha}$

inelasticity: $\kappa \propto \kappa_0 \cdot E^{-\omega}$

$$X^{\mathrm{A}}_{\mathrm{max}} = X^A_1 + X_0 \ln \frac{\kappa E}{A \cdot 2N\xi^{\pi}_{\mathrm{c}}} =$$

$$X^A_1 + (1-\alpha-\omega)\cdot(X_0 \ln \frac{E}{A\cdot\xi^{\pi}_{\mathrm{c}}}) + X_0 \cdot (\ln\kappa_0 - \ln N_0)$$

$$\begin{matrix}\kappa_0 \rightarrow f_{\kappa}\kappa_0 \\ N_0 \rightarrow f_N N_0\end{matrix} \quad \Rightarrow \quad X^A_{max}{}' = X^A_{max} + X_0(\ln(f_{\kappa}) - \ln(f_N))$$

MOCHI (preliminary)

[PoS(ICRC2023)245]

“changing the shape of energy dependence“ ➔ mass-dependent modifications